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The Effects of Electron Beam Radiation on Paper

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THE EFFECTS OF ELECTRON BEAM RADIATION ON PAPER

by

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ABSTRACT

The objectives of this investigation were as follows:

1. To see the general effects of electron beam radiation on paper,
2. To see the effect of varying lignin content of paper as it pertains to electron beam radiation,
3. To see the effects of possible protecting compounds.

It was clearly shown by this investigation that electron beam radiation has detrimental effects on paper. Decreases in brightness, tensile, tear, burst, and fold were observed along with an increase in yellowness. It was also shown that the greatest percentage of damage occured during low dosage (<2 Mrad); and that as the dose was increased, the rate of damage decreased.

The investigation also showed that as the amount of lignin in paper increases or decreases, there is no general trend for brightness, tensile, tear, burst, and fold to increase or decrease.

The investigation also showed that the three chemicals, Tinuvin 328, Tinuvin 292, and Irganox 1010 from the Ciba-Geigy Corp. only protect the sheet at addition levels above 2% addition and have a detrimental affect below 2% addition. Up to a 20% increase in strenth was observed at 5-7% addition levels. The chemicals were also detrimental inthat they hurt the brightness and yellowness.

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INTRODUCTION

As the cost of energy increases, the demand for more energy-efficient processes takes place. Radiation curing of polymer coatings and adhesives is one of these new, energy-efficient processes.

Radiation curing involves exposing a reactive monomer and oligmer systems to radiation, usually electron beam or ultra-violet radiation. The radiation causes the monomers and oligmers to polymerize producing a finished product. Radiation curing is so energy efficient because it doesn't have to drive off any solvents as is done with conventional coating and adhesives.

One problem of this technique is that the effect of the radiation on paper has not been studied. Therefore, it is the purpose of this investigation to see the effects of electron beam radiation on paper.

BACKGROUND

Electron Beam Radiation

Electron beam radiation involves exposing a substrate to accelerated, high energy electrons. Transformers are used to step-up and rectify normal line voltage into high DC voltage. An electron accelerator and the high DC voltage are used to create electrons and accelerate them into the substrate(1). The accelerated high energy electrons are used to break bonds and create free-radicals for polymerization.

Uses

Radiation curing is mainly used in the lumber, printing and paper industries. In the lumber industry, radiation curing is mainly used in the production of particle board, paneling, and similar products. In the printing industry, radiation is used to cure polymer inks. In the paper industry, radiation curing is used with coatings, adhesives, and laminations.

The adhesives, inks, laminations, and coatings used in radiation curing are made of reactive monomer and oligimers systems. The monomers and oligimers are usually polyfunctional vinyl acetates. Being polyfunctional there is a high degree of cross-linking in the cured polymer. Curing takes place by means of free-radical polymerization. The high energy electrons of the electron beam create free-radicals at some of the functional groups. The free-radicals then initiate rapid polymerization of the entire system(1,2,3).

Electron Beam Versus Other Radiation

Electron beam radiation has many advantages over other forms of radiation curing. The accelerated electrons from electron beam radiation are advantageous in that they ionize on contact and not by secondary mechanisms. X-rays and gamma-rays work by secondary mechanisms, where the radiation is first absorbed by molecules and then an electron is expelled from the molecule(4). This makes electron beam radiation faster and more direct. Ultra-violet light radiation can also be used in radiation curing. Electron beam radiation is a higher energy radiation than ultra-violet light radiation. Because of this, electron beam radiation can cure thicker coatings and penetrate through materials to cure internal adhesives or underlying laminations better than ultra-violet light radiation can. This also allows electron beam radiation processes to run faster. Since ultra-violet light is a fairly low energy radiation, photo-initiators have to be used in the coating and adhesives to create the free radicals for polymerization to take place. Photo initiators are not necessary in electron beam curing(1,2). Electron beam curing costs less than ultra-violet radiation curing.

Advantages

The major advantage of radiation curing is that it requires a lot less energy to radiation cure polymer coatings and adhesives than it does to volatilize conventional coatings and adhesives. Presently, one to two megarads of electron beam radiation are required to polymerize coatings. One megarad is equivalent to 4.3 BTU per pound. To volatilize a conventional coating of the same weight, several hundred BTU per pound would be required(1). Electron beam radiation devices are also advantageous in that they take up a lot less room than conventional drying systmes

Electron beam curing is advantageous in that there are no volatiles or exhaust gases to deal with as there are in conventional solvent based systems. This means that less pollution control equipment(1).

The coatings, laminations, inks, and adhesives have many advantages. They bind strongly to the substrate and are highly cross-linked, which makes them inert and resistant to solvents and rabbing. Since there are no solvents in the coatings, laminations, inks, and adhesives, there is very little shrinkage; therefore, what is put down is what you get. It has also been found that the coating and inks produce better quality jobs and give up to 25 percent more mileage as compared to conventional inks and coatings(1).

Disadvantages

There are several disadvantages with these radiation-polymer systems. The major problem is, since the polymers are so cross-linked and bind so strongly to the substrates, that they cannot be repulped(1).

Also, there are several safety hazards. When the high energy electrons hit matter, x-rays can be produced. These must be protected against. The high energy electrons can also create ozone from oxygen. This hazard is usually minimized by flushing the irradiation zone with nitrogen. The reactive monomers and oligimers can also be skin and eye irritants before they are irradiated(2).

Another disadvantage is that there has been very little research as to the effects of electron beam radiation on paper.

Cellulose Research

Radiation has been used for many years in the textile industry to create free radicals for grafting and copolymerizing of cellulose. Since paper is very similar to cellulose, the effects of radiation on paper should also be very similar.

A study by Delides(9) using a scanning electron microscope found ionizing radiation, like election beam, to generate cracks in the fiber wall along a spiral angle. These were found at doses of one megarad or greater; and as the dose was increased, the cracks widened, deepened, and new cracks formed. Delides concluded that the crack generation was probably due to the breaking of molecular bonds.

Many studies(5-15) have found decreases in the strength, viscosity, and crystallinity of cellulose from radiation. Delides(8) found an exponential decrease in the tensile strength which followed the equation:

$$Y = Y_o \ \exp\ (-R/R_o$$

where Y_o and Y were the elongation at break before and after irradiation of R Mrad, respectively. Viscosity was also found to follow an exponential decrease.

The decrease in tensile, viscosity, and crystallinity are believed to be from the breaking of cellulose chains. This is believed to be caused from oxidative depolymerization where the radiation in the presence of oxygen creates free-radicals on the cellulose chain. The free-radicals lead to chain scissions.

Protection

Research by Guthrie and others(4,5, 25,26) has shown that a substitution of an aromatic group onto the cellulose would protect the cellulose. It is believed that the aromatic groups lead to selective absorption of the incident radiation and the description of the absorbed radiation by conversion to heat energy.

EXPERIMENTAL PROCEDURE

General

This investigation of the effects of electron beam radiation on paper was divided into three parts; as follows:

1. To see the general effect of electron beam radiation on several papers,
2. To see the effects of varying lignin content as it pertains to electron beam radiation,
3. To see the effects of addition of several possible protective compounds.

Paper Samples

Both commercial grades and laboratory prepared handsheets were used in these experiments. The commercial grades used were a 50 lb. bag paper and a 34 lb. waterleaf paper from the James River Company of Kalamazoo, Michigan. The handsheets were made from cotton linters, Espanola bleached softwood, Chesapeake unbleached kraft softwood, or news blanks. The news blanks were composed of 82% groundwood and 18% sulfite softwood.

The pulps for the handsheets were all refined to 300 canadian standard freeness in a laboratory Valley Beater using 360 grams oven dry basis pulp and enough water to make 23 liters total. The beater was weighted with 5,500 grams.

After refining, handsheets were formed in a laboratory Noble and Wood handsheet mold, which is 8" by 8", on a normal handsheet screen. The weight of the handsheets was 2.5 g +0.1 g (60 g/m^2). The handsheets were pressed between felts and dried with a laboratory, steam filled dryer can at 240°F.

Chemicals

Three compounds were used in the attempt to protect the paper from electron beam radiation. These compounds were Tinuvin 328, Tinuvin 292, and Irganox 1010 from the Ciba-Geigy Corporation of Ardsley, New York. These compounds are normally used in coatings and act as U.V. absorbers, light stabilizers, heat stabilizers, antioxidants, and free radical scavengers. The Tinuvin 328 is a hydroxyphenyl benzotriazol. The Tinuvin 292 is a hindered amine. The Irganox 1010 is a hindered phenolic compound. Their structures are shown in Figure 1. These compounds are organic; so that in order to apply them to the paper, they had to be dissolved in an organic solvent. Ethyl acetate was used because it is a common solvent to all three compounds.

Irradiation

The papers used in the three experiments were treated with electron beam radiation at Energy Sciences, Inc. of Woburn, Massachusetts by E.P. Tripp III and his staff.

The papers were irradiated at three different dose levels, namely; 2 Mrad, 5 Mrad, and 10 Mrad. They were run through an elect on curtain at a line speed of 22 feet per minute and a terminal voltage of 200 kilovolts.

The irradiation zone was flushed with nitrogen at 400 cubic feet per hour to minimize ozone generation.

Paper Testing

The irradiated papers were tested for brightness, yellowness, tensile, tear, burst, and fold. The brightness was tested according to Tappi standard T452 and is reported in percent. The yellowness was tested with a L.A.B. meter, using the B-reading to indicate the yellowness. An increase in the B-reading shows an increase in the yellowness. The tensile was tested on an Instron Tensile Tester using a one inch strip of paper. The jaw span was five centimeters and moved at a rate of two centimeters per minute. Tensile is reported as kilograms required to break a one-inch strip. Tear was tested on an Elmendorf Tear Tester according to Tappi standard T414 and is reported in grams to tear one sheet. Burst was tested according to Tappi standard T403 and is reported in p.s.i. Fold was tested on a MIT Tester according to Tappi standard T511 and is reported in cycles.

Procedure

To see the general effects of electron beam radiation on paper, the two commercial grades and the handsheets were irradiated and tested.

To see the effects of lignin as it pertains to electron beam radiation, the handsheets of varying lignin content were irradiated and tested. Kappa numbers were used to show the varying amounts of lignin in the bleached softwood, unbleached softwood, and groundwood. The Kappa number of the cotton linters was taken as zero. The Kappa numbers of these pulps were measured according to Tappi standard T236.

To see the effects of the Ciba-Geigy chemical inhibitors as they pertain to electron beam radiation, the commercial, 34 lb. waterleaf paper was coated with varying amounts of the inhibitors, then irradiated, and tested. The treated papers were then compared to the untreated papers. To apply the inhibitors, the inhibitor compounds were first dissolved in ethyl acetate in varying concentrations. The waterleaf paper was then dipped into the solution; and a blade drawdown was done on the paper to get a uniform addition. A drawdown with pure ethyl acetate was also done to see if it had any affect. A comparison of T328 to T292 was also made by varying the percentage of each in several samples at 2% total addition. The varying concentrations used were: 100/0, 75/25, 50/50, 25/75, and 0/100 of T328/T292.

The results of the testing and the percentages of the various inhibitors are shown in the appendixes.

RESULTS

General Effects

In the first experiment, the general effects of electron beam radiation on paper were shown.

Figure 2 shows the effects of an increasing dose of electron beam radiation on yellowness. The graph shows a significant increase in the B-readings as the dose increased; thus, there is an increase in the yellowness as the dose increase.

Figure 3 is a graph showing the effects of an increasing dose of electron beam radiation on brightness. This graph shows that there is a decrease in the brightness as the dose of radiation is increased. It also shows a more rapid decrease in brightness at the lower radiation levels than at the higher radiation levels. Thus, most of the damage occurs at the lower radiation levels; and as the dose increases, the rate of decrease in brightness becomes less and less.

Figures 4, 5, 6, and 7 show the effects of increasing electron beam radiation on several strength properties of papers. The properties of tensile, tear, burst, and fold are shown in these graphs. Like brightness, all of these properties showed a significant decrease as the radiation dose increased. The graphs also show, as did the brightness graph, a more rapid decrease in the strength at the lower dose levels than at the higher dose levels.

The Effects of Lignin

To observe the effects of varying lignin content as it pertains to electron beam radiation, the handsheets made from the cotton linters, bleached softwood, unbleached softwood, and news blank had to be compared. To make comparisons, the percentage decrease in the paper property of the irradiated papers as compared to the untreated paper was graphed against the electron beam radiation dose. The percent decrease in brightness, tensile, tear, burst and fold versus radiation dose is shown in Figures 8 through 12.

Figure 8 shows the graph of percent decrease in brightness versus radiation dose. This graph shows no general trend in the percent decrease in brightness for the papers of increasing lignin content, namely; from cotton to bleached softwood to unbleached softwood to groundwood. This shows that the lignin is not the only factor that is causing the decrease in brightness.

Figures 9, 10, 11, and 12 show the percent decrease in tensile, tear, burst and fold, respectively, versus the radiation dose. Although there were some significant differences between some handsheets, all of the strength properties showed no general trend for the papers of increasing lignin content to either increase or decrease. the strength. Therefore, the lignin content is not significantly affecting the strength properties in relationship to electron beam radiation.

Inhibitors

In the third experiment, the effects of three possible protective compounds were observed. The testing of the ethyl acetate blank showed no difference from the untreated samples; therefore, the ethyl acetate solvent was not an influence in any of the observed results. The effects of the three inhibitors, T328, T292 and I1010, are shown in Figures 13 through 28.

Figure 13 shows the effects of increased percent inhibitor on yellowness. The graphs show a significant increase in the yellowness as the percentage of inhibitor is increased. This is obviously a detrimental effect of the inhibitors. All of the inhibitors tested resulted in an approximately equal increase in yellowness.

Figures 14, 15 and 16 show the effects of increased percent inhibitor on brightness at the 2, 5 and 10 megarad levels respectively. These graphs all show a decrease in the brightness as the percentage of inhibitor is increased. This is also a detrimental effect of the inhibitors.

Figures 17, 18, and 19 show the effects of increased percent inhibitor on the tensile strength at the 2, 5, and 10 megarad levels respectively. All of these graphs show a small decrease in tensile strength at the 0.5% inhibitor level as compared to the uncoated sheet. From this decrease at 0.5% inhibition, the tensile strength increases steadily. At approximately 20% inhibitor, the sheet has the same strength as the uncoated, original paper. Above the 2% level of inhibitor, the strength continues to increase displaying the significant protection of the paper by the inhibitors.

Figures 20, 21, and 22 show the effects of increased percent inhibitor on the internal tearing resistance of the paper at the 2, 5, and

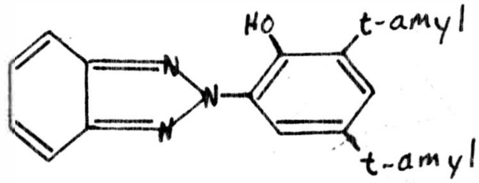
10 megarad levels. Like the tensile, there is a decrease in the tear at the low levels of percent inhibitor; and as the percent inhibitor increases so does the tear strength. Unlike the tensile, the tear strength does not reach the strength of the uncoated paper until about 3 to 4% inhibitor and then has higher strength.

Figures 23 through 28 show the effects of increased percent inhibitor on the bursting strength at 2, 5, and 10 Mrad and the folding endurance at 2, 5, and 10 Mrad of electron beam radiation. The burst and fold behaved similarly like the tensile; that is, the strength was slightly below the uncoated sample at 0.5% inhibitor, the same as the uncoated sample at approximately 2% inhibitor and greater than the uncoated sample above 2% and increasing as the percent inhibitor increased.

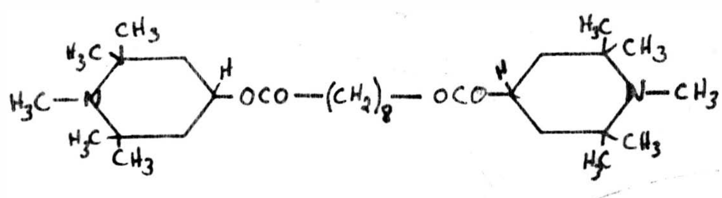
T328 Versus T292

A comparison of Tinuvin 328 to Tinuvin 292 was also made. This comparison was made by testing 2% inhibited samples that contained varing percentages of T328 to T292; namely, 100/0, 75/25, 50/50, 25/75, and 0/100. Figures 29 through 34 shows the effects of the varied concentrations of T328 to T292 for yellowness, brightness, tensile, tear, burst, and fold. As can be seen in the graphs, there is no general trend for either T328 or T292 to significantly improve the yellowness, brightness, tensile, tear, burst or fold as percentage increases.

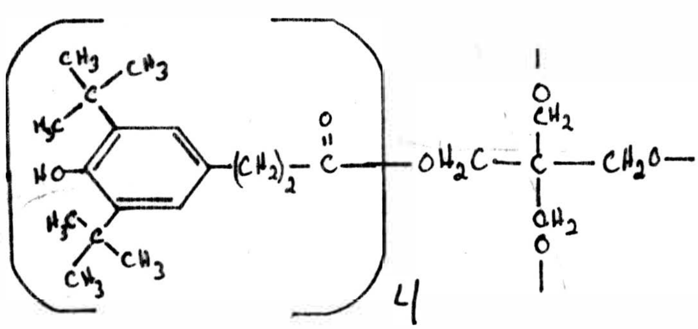
Figure 1 :



Tinuvin 328



Tinuvin 292



Irganox 1010

Figure 2: B readings vs. Dose

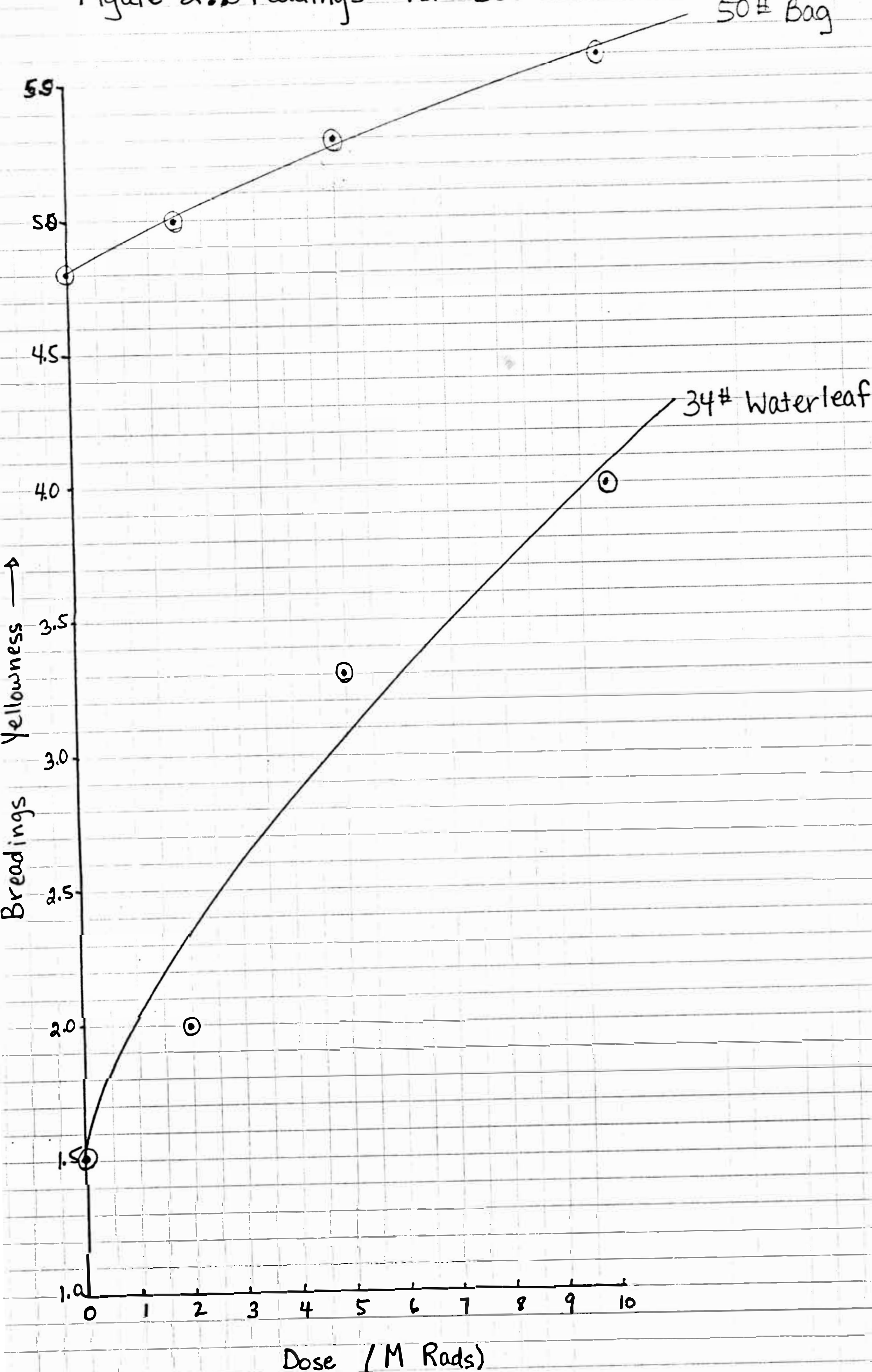


Figure 3: Brightness vs. Dose

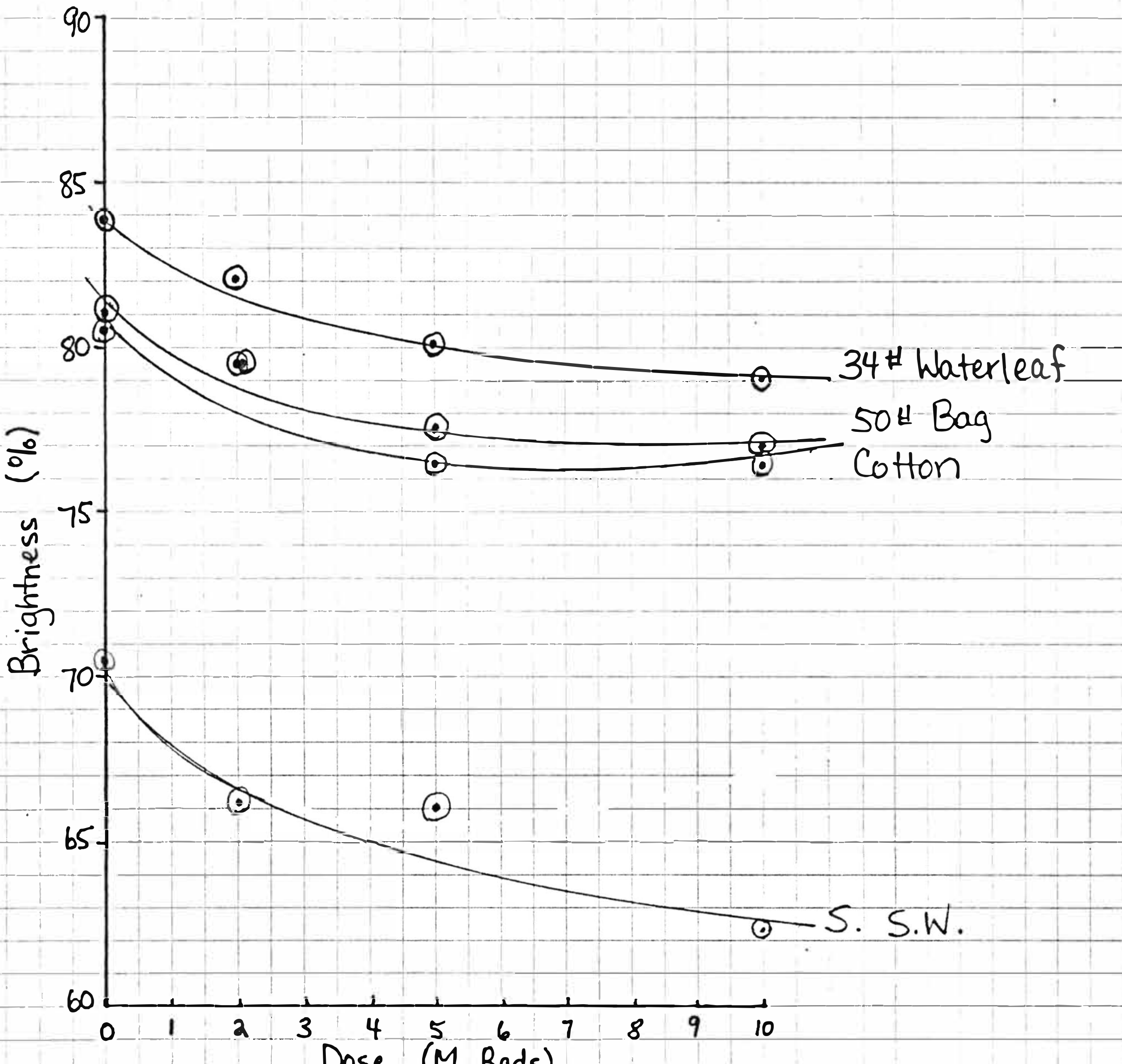


Figure 4: Tensile vs. Dose

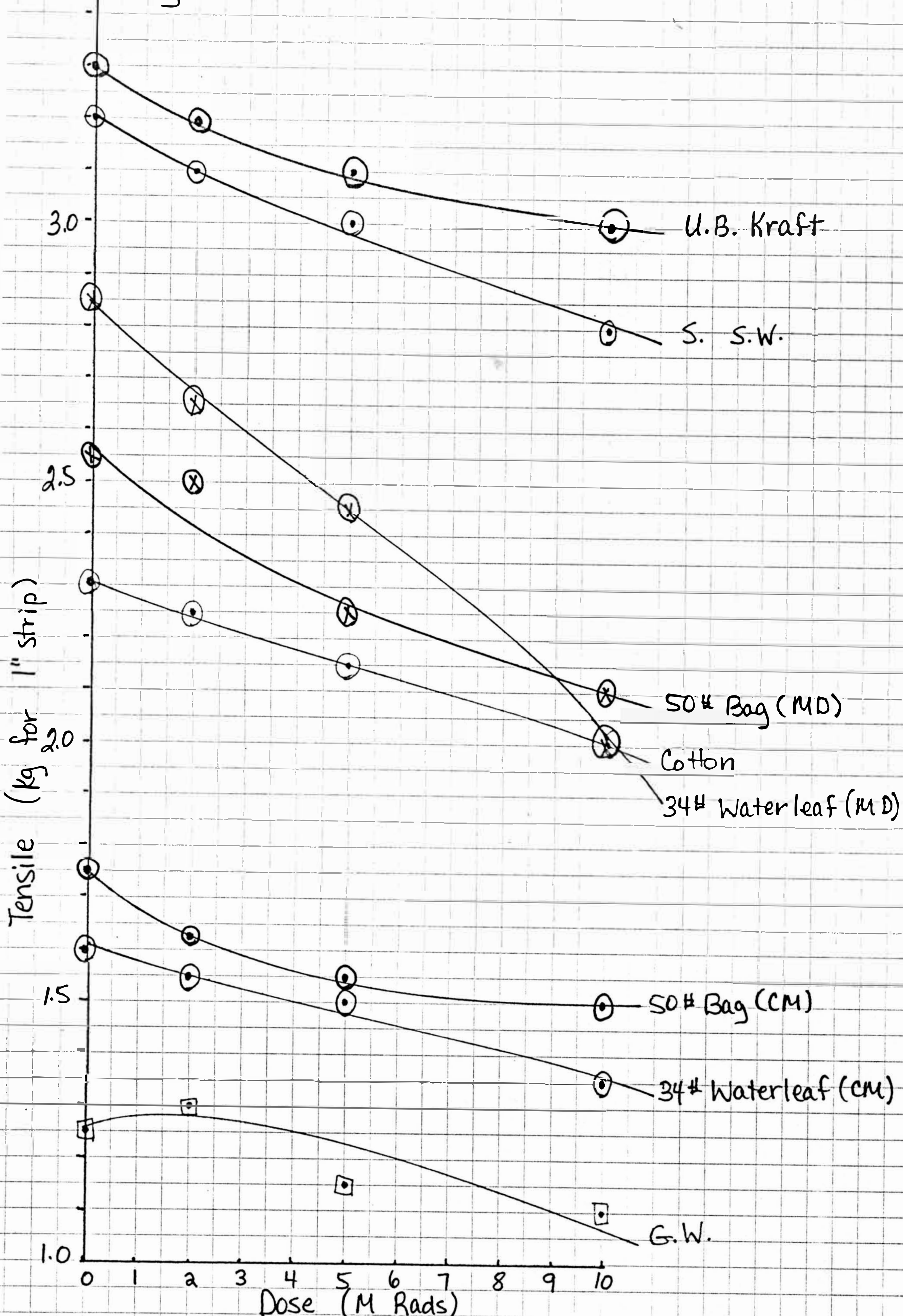


Figure 5: Tear vs. Dose

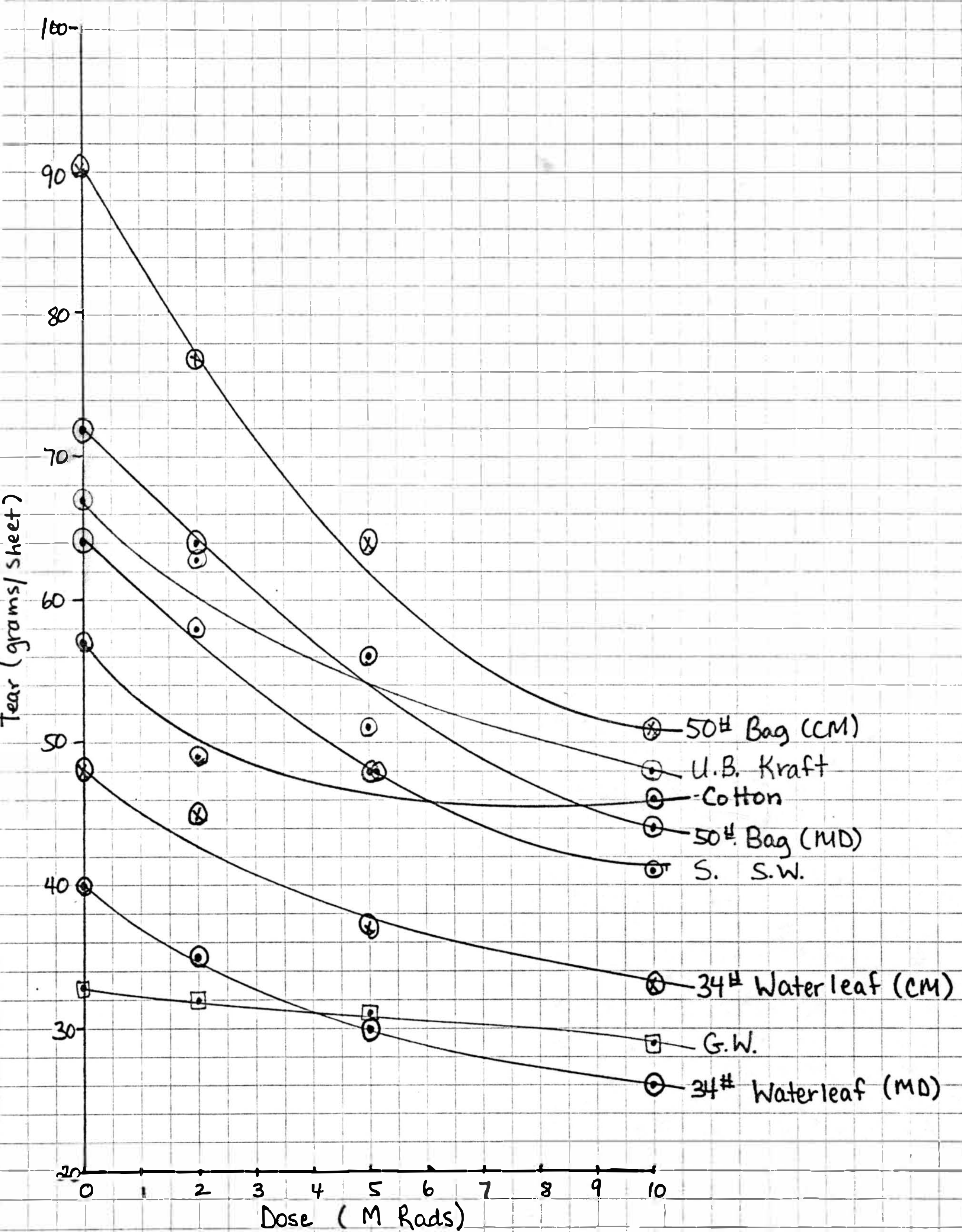


Figure 6: Burst vs. Dose

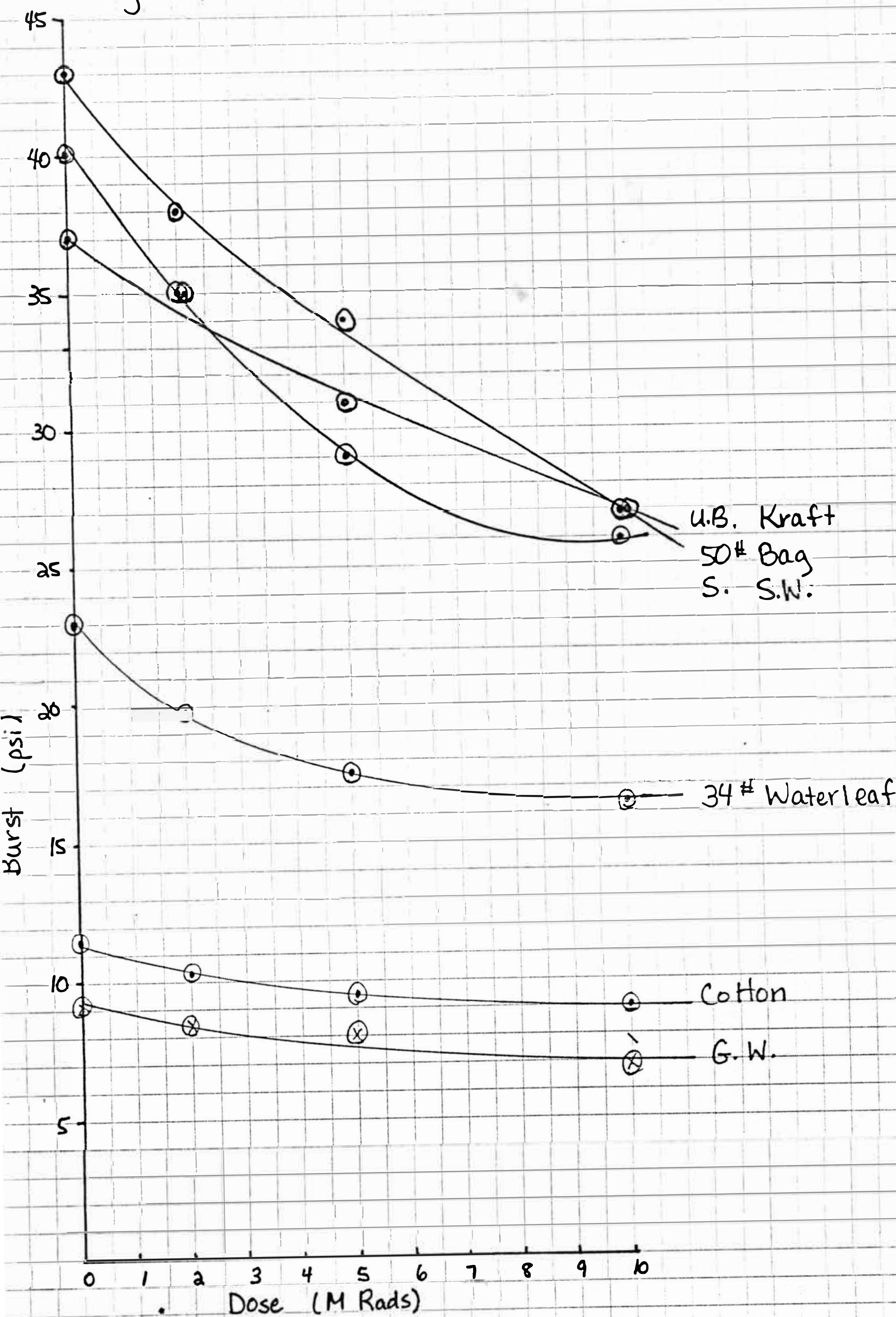


Figure 7: Folding Endurance vs. Dose

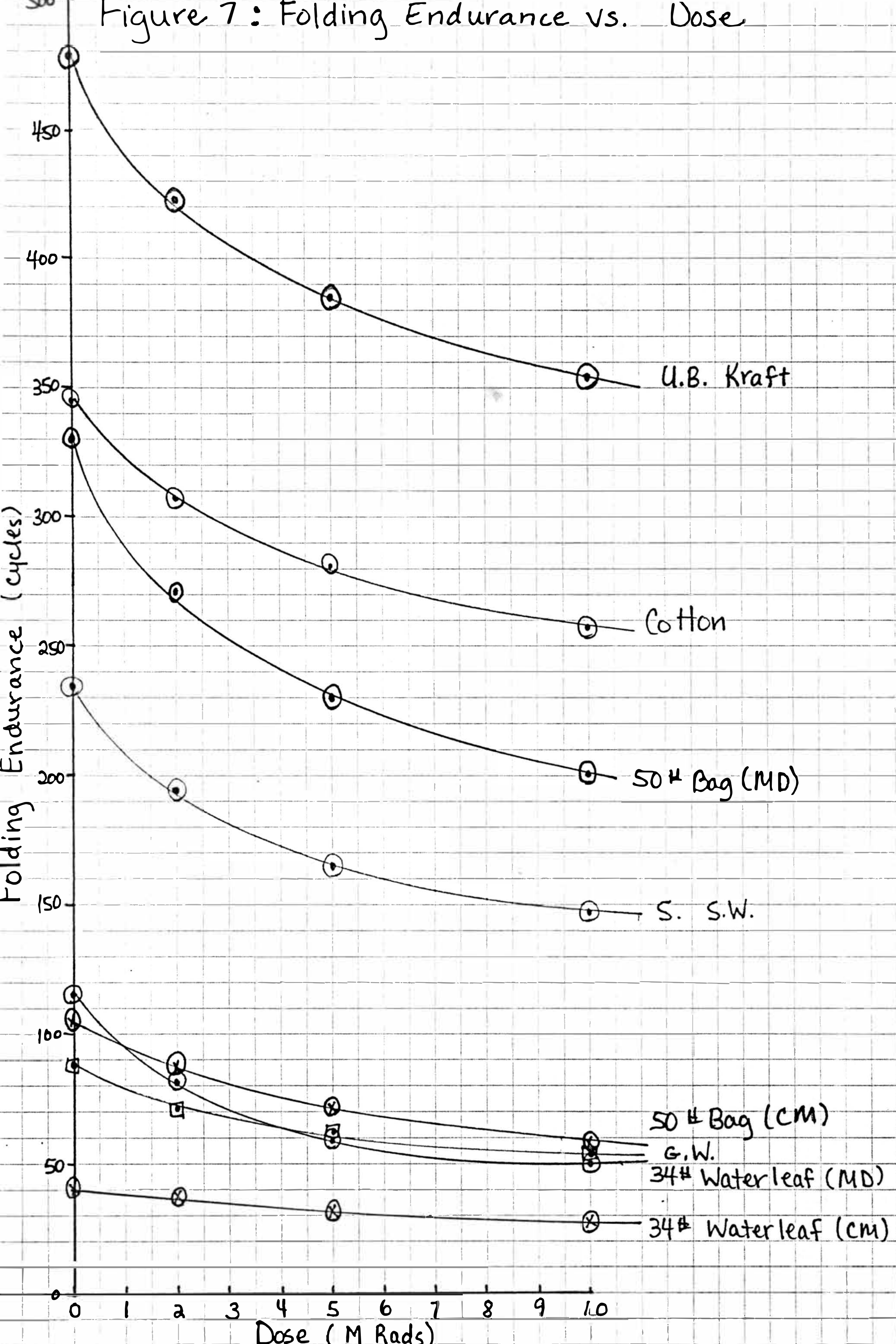


Figure 8 : % Decrease in Brightness vs. Dose

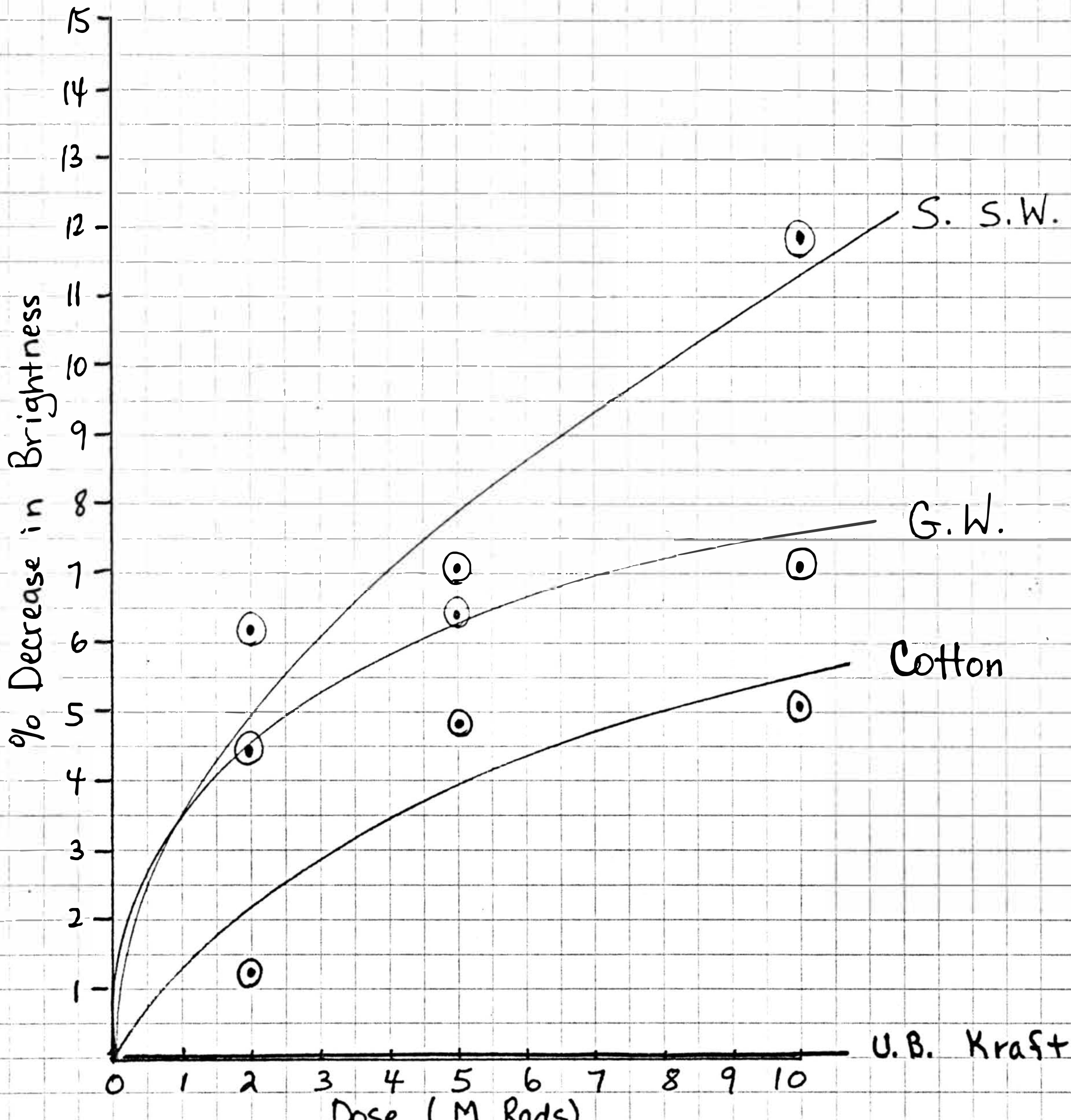


Figure 9 : % Decrease in Tensile vs. Dose

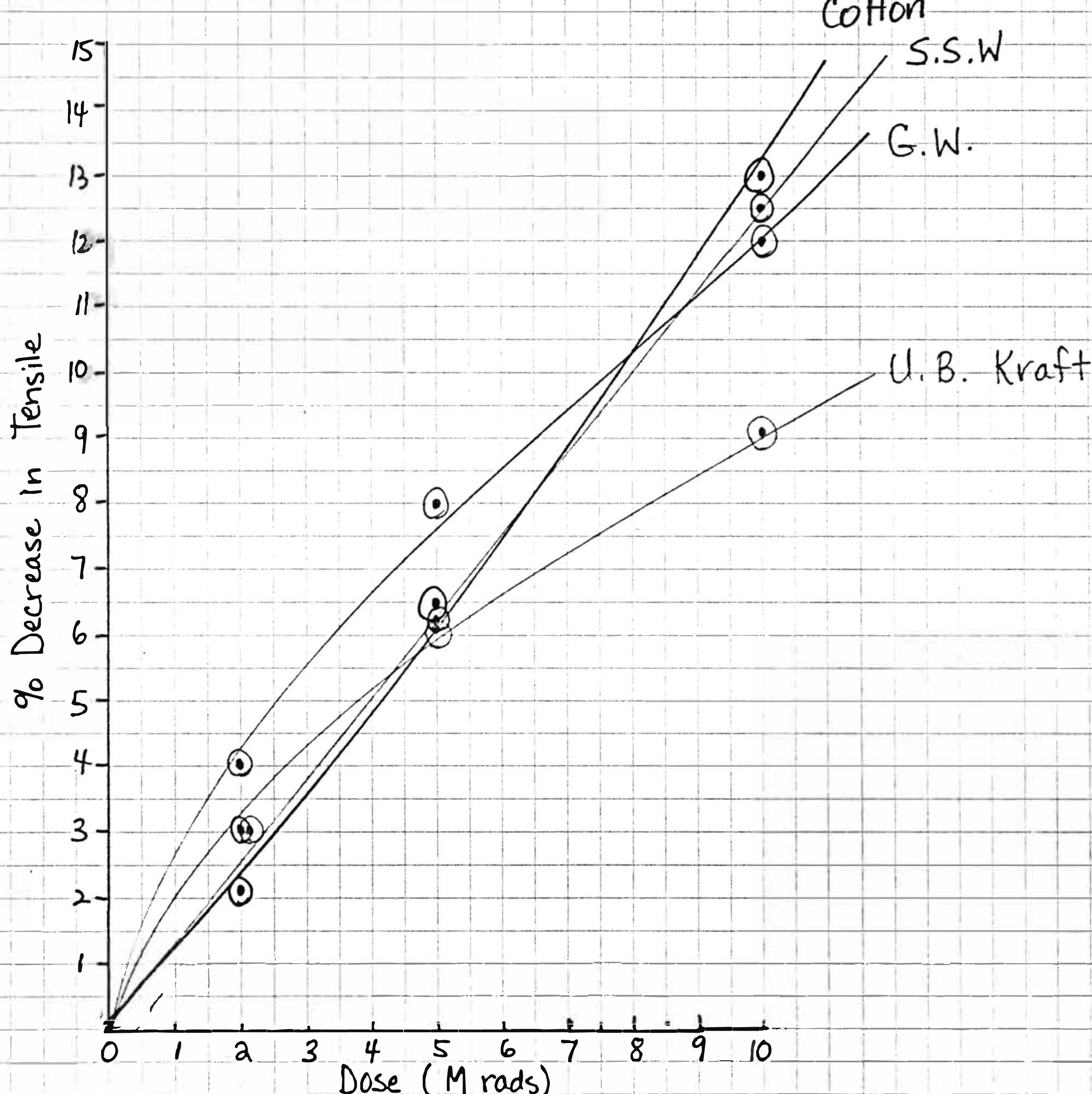


Figure 10: % Decrease in Tear vs. Dose

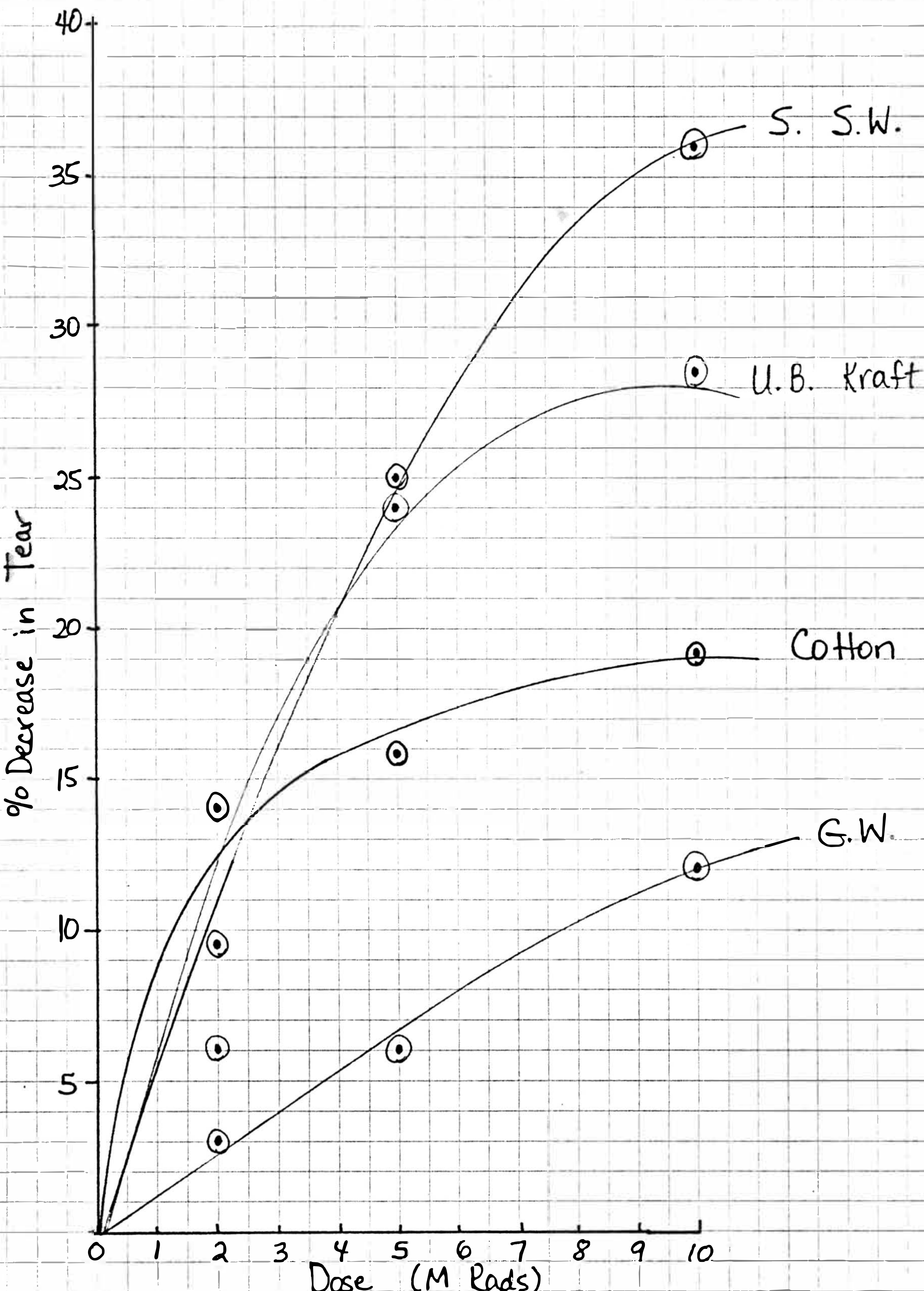


Figure 11 : % Decrease in Burst vs. Dose

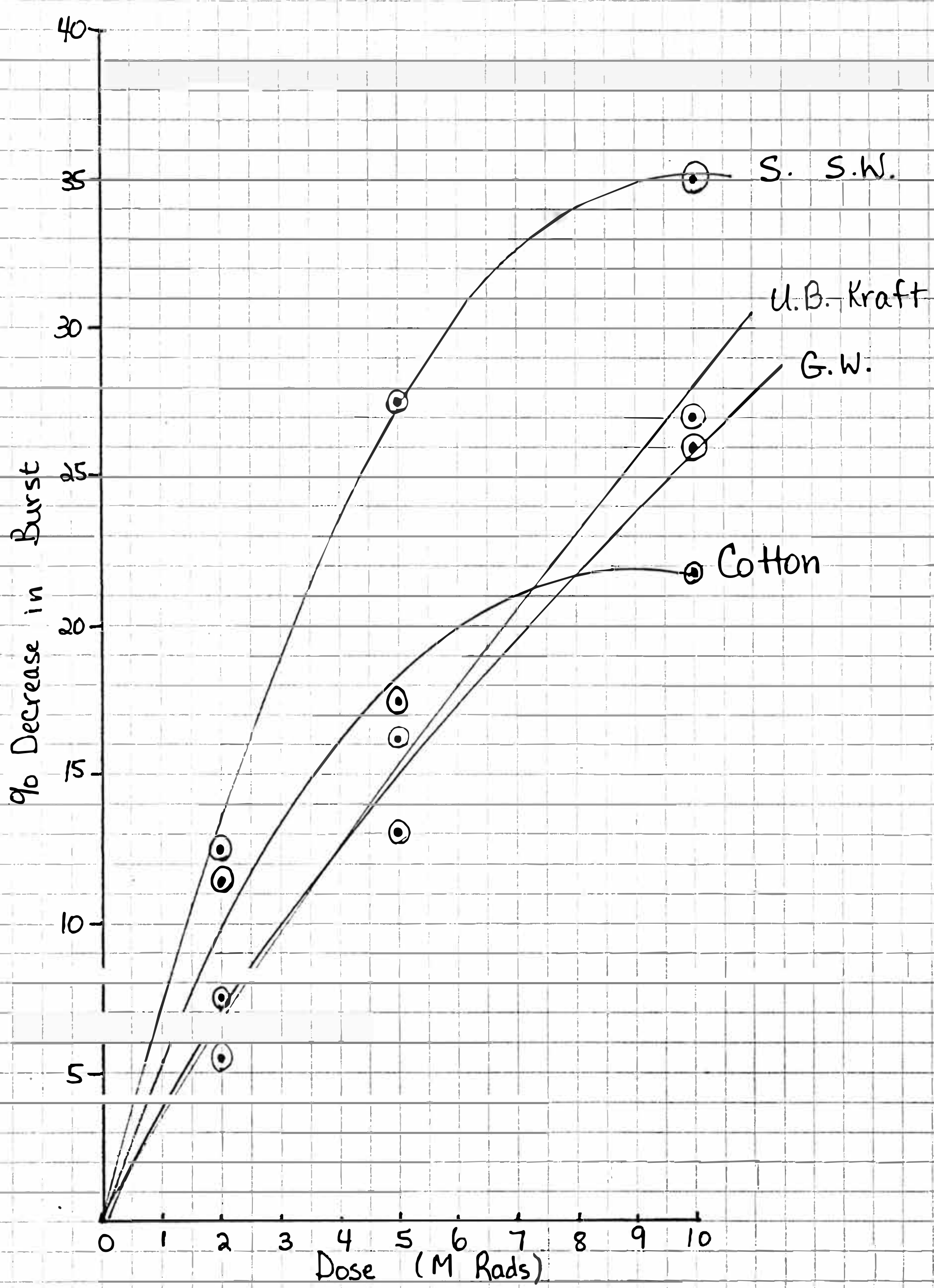


Figure 12 : % Decrease in Fold vs. Dose

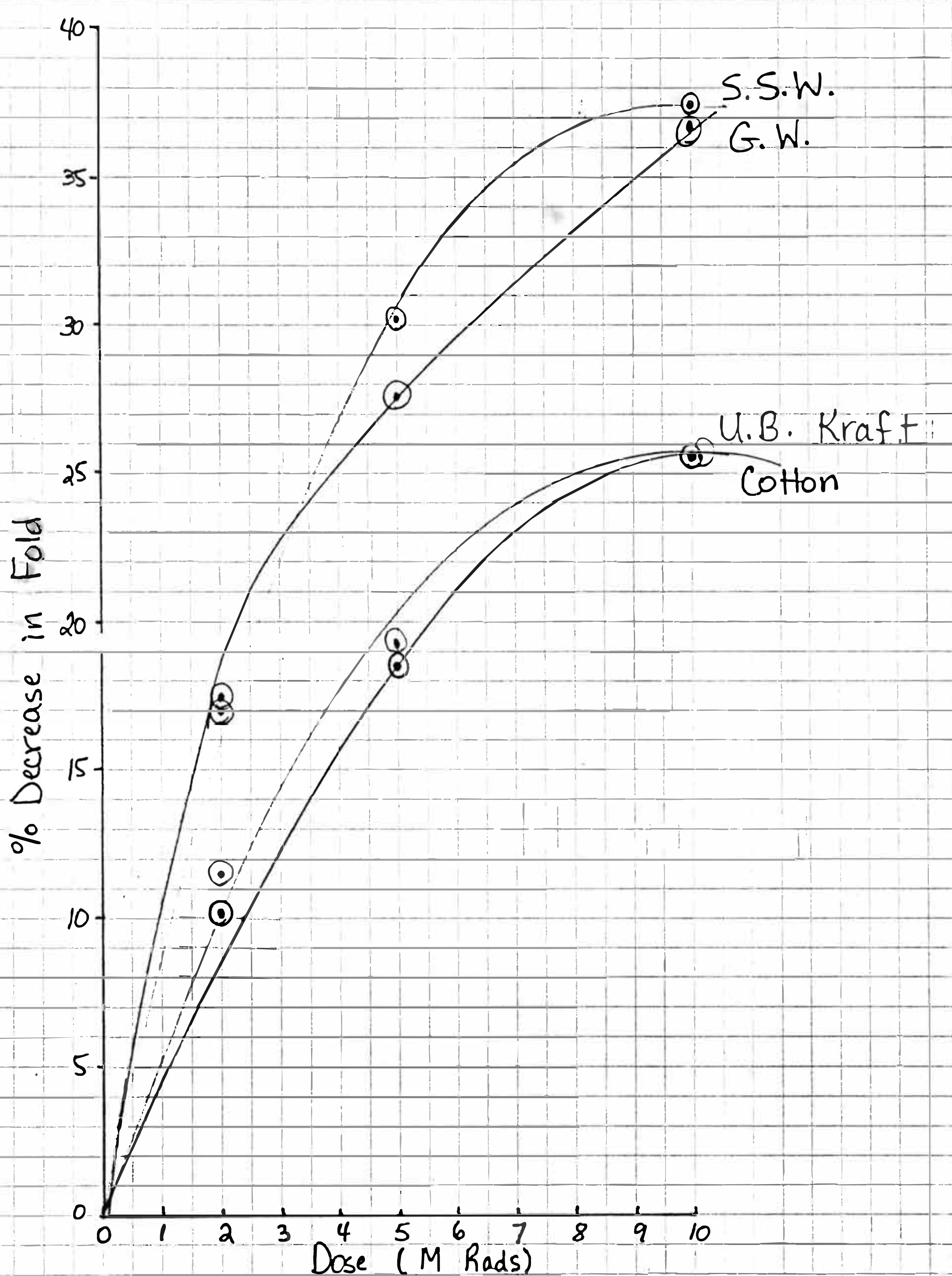


Figure 13: Yellowness vs % Inhibitor

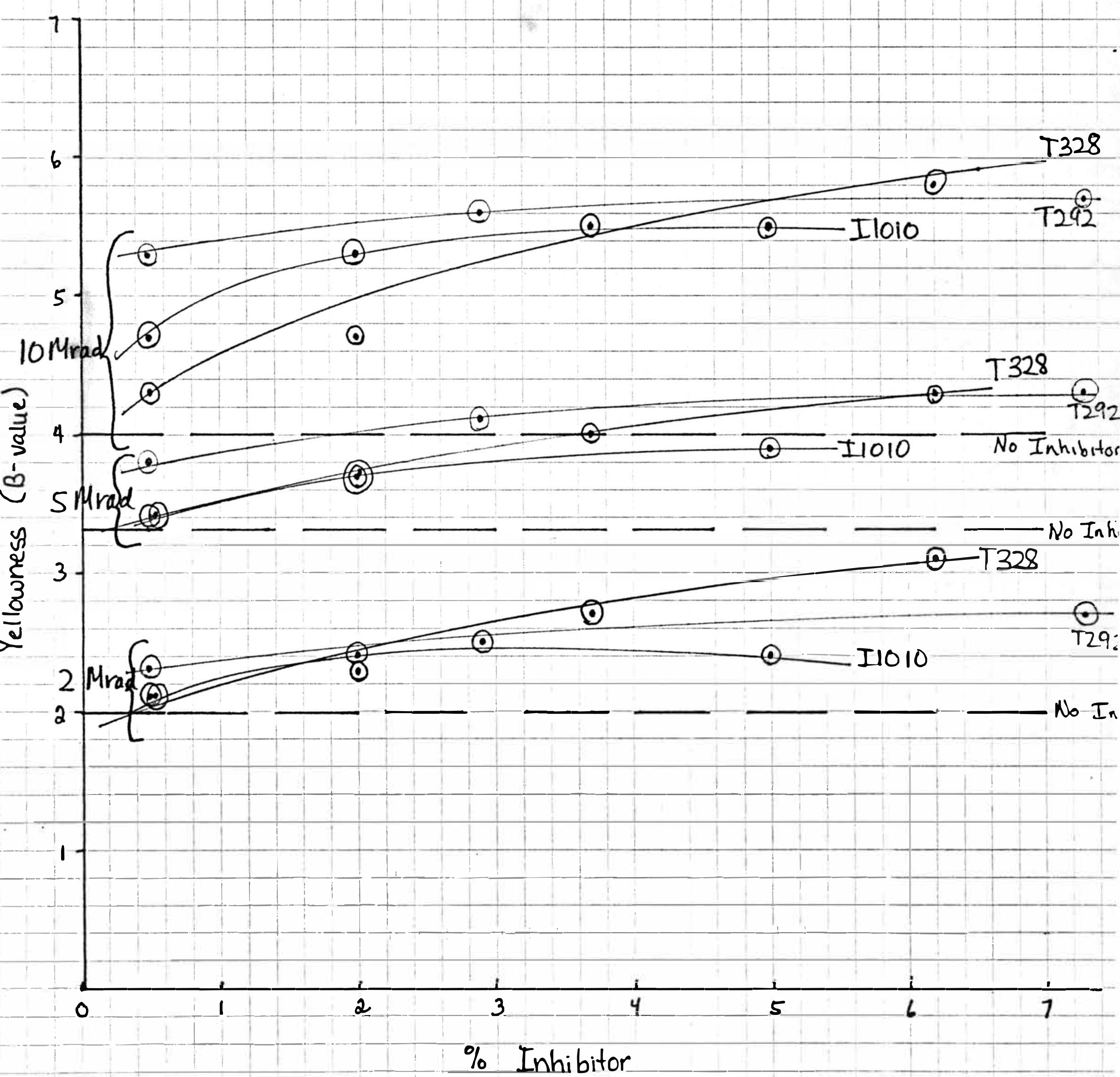


Figure 14: Brightness vs. % Inhibitor
(2 M rad)

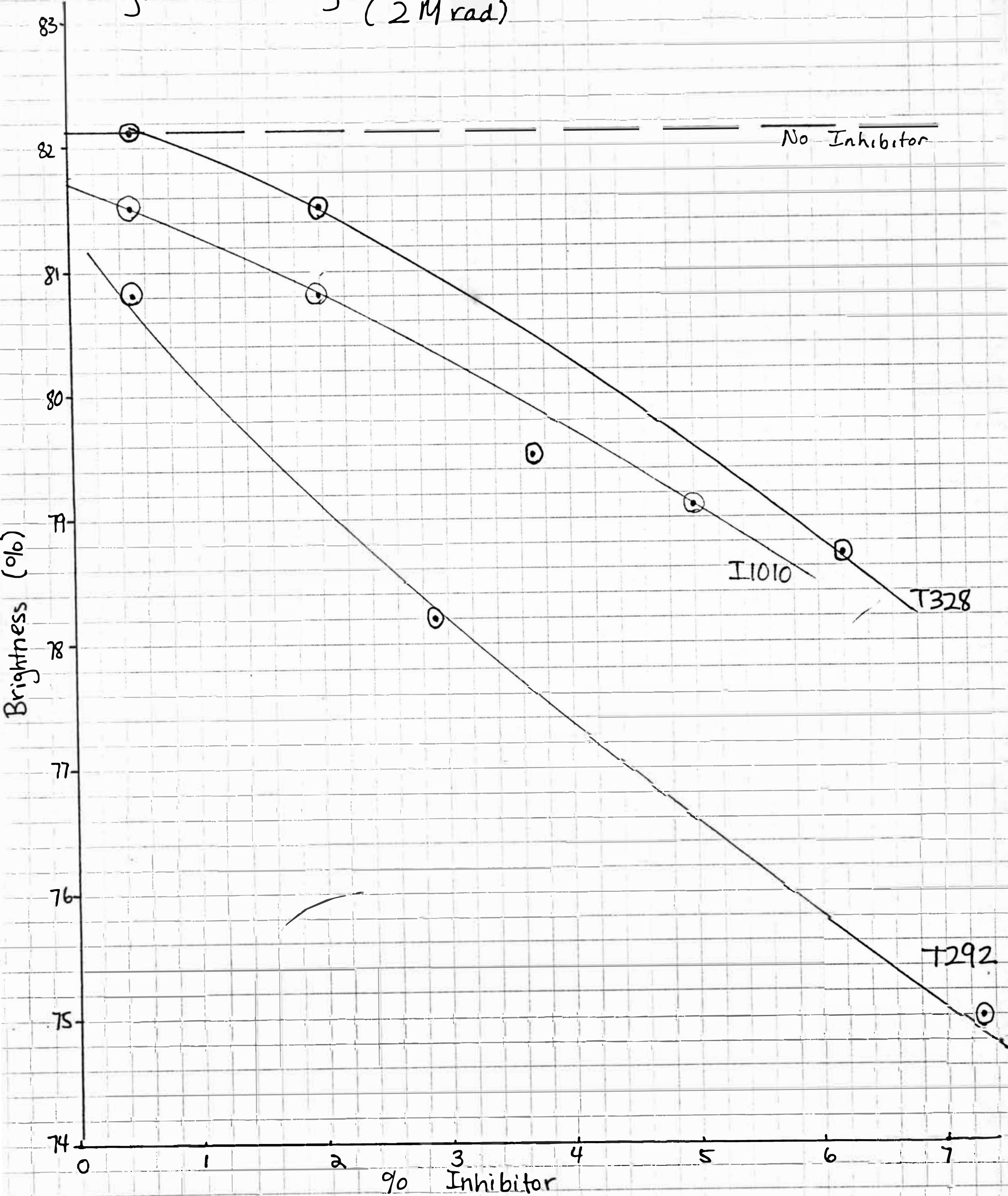
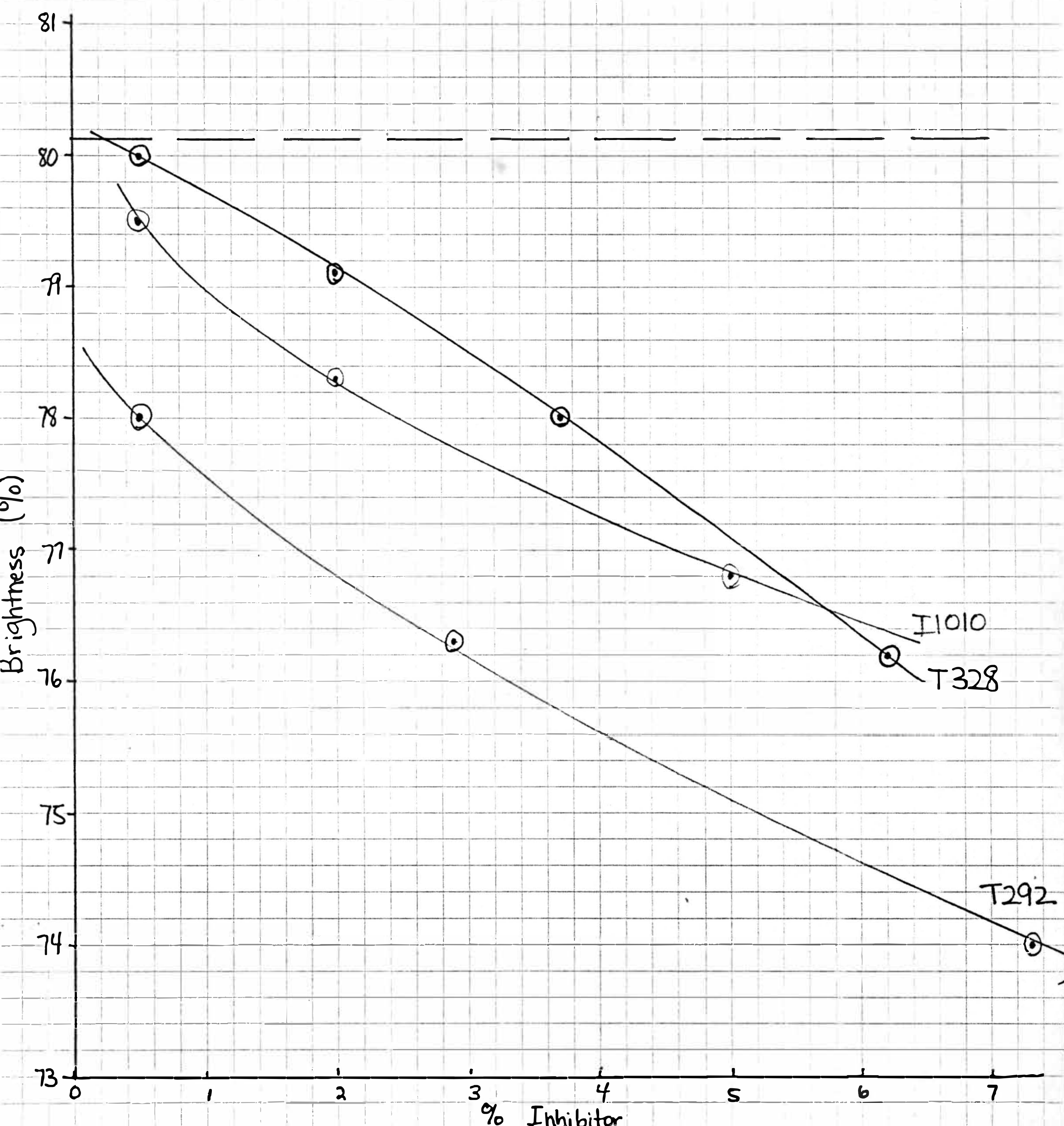
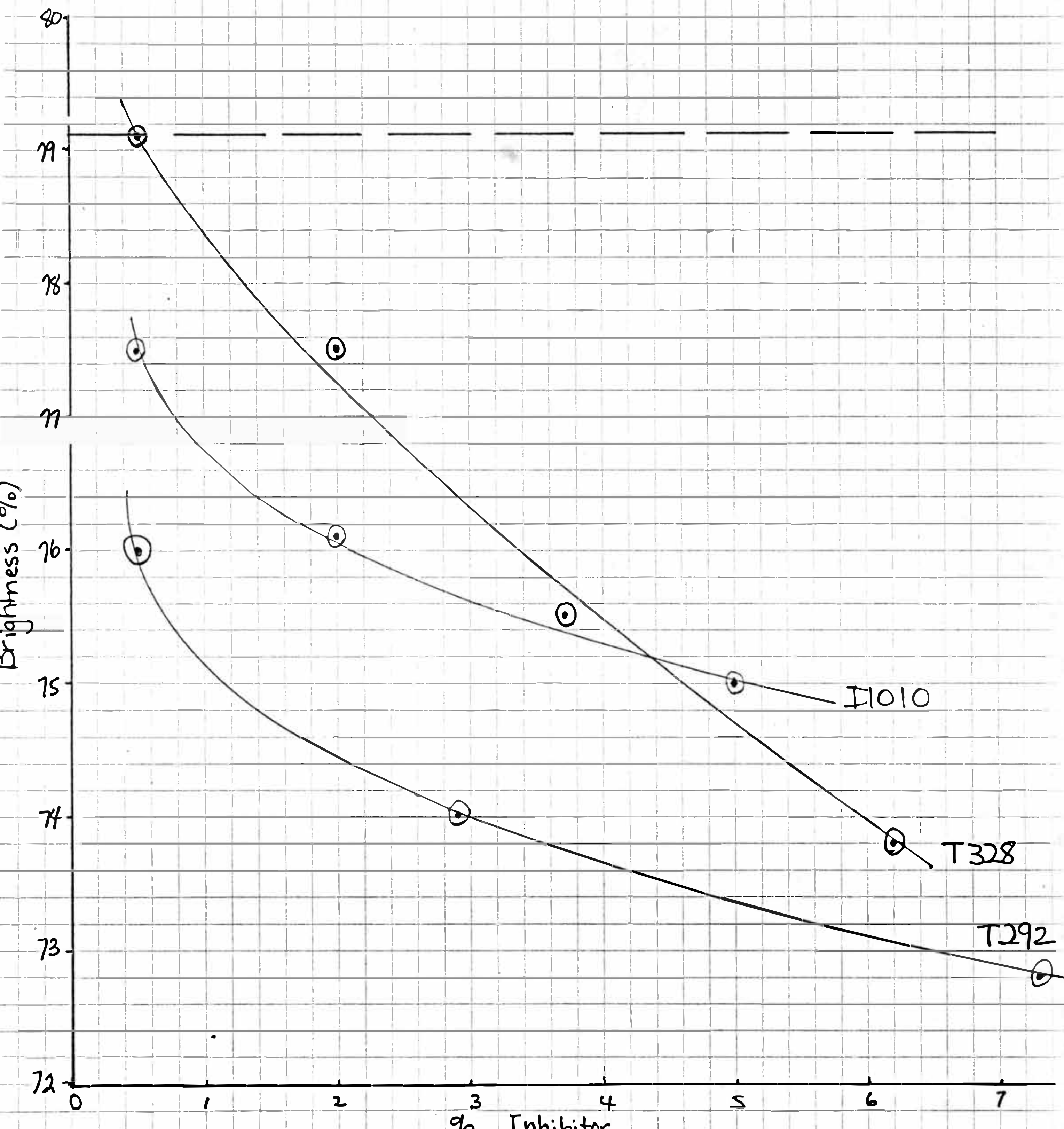


Figure 15 : Brightness vs. % Inhibitor
(5 Mrad)



10 M rad

Figure 16 : Brightness vs. % Inhibitor
(10 M rad)



2 M rad

Figure 17: Tensile vs. % Inhibitor
(2 M rad)

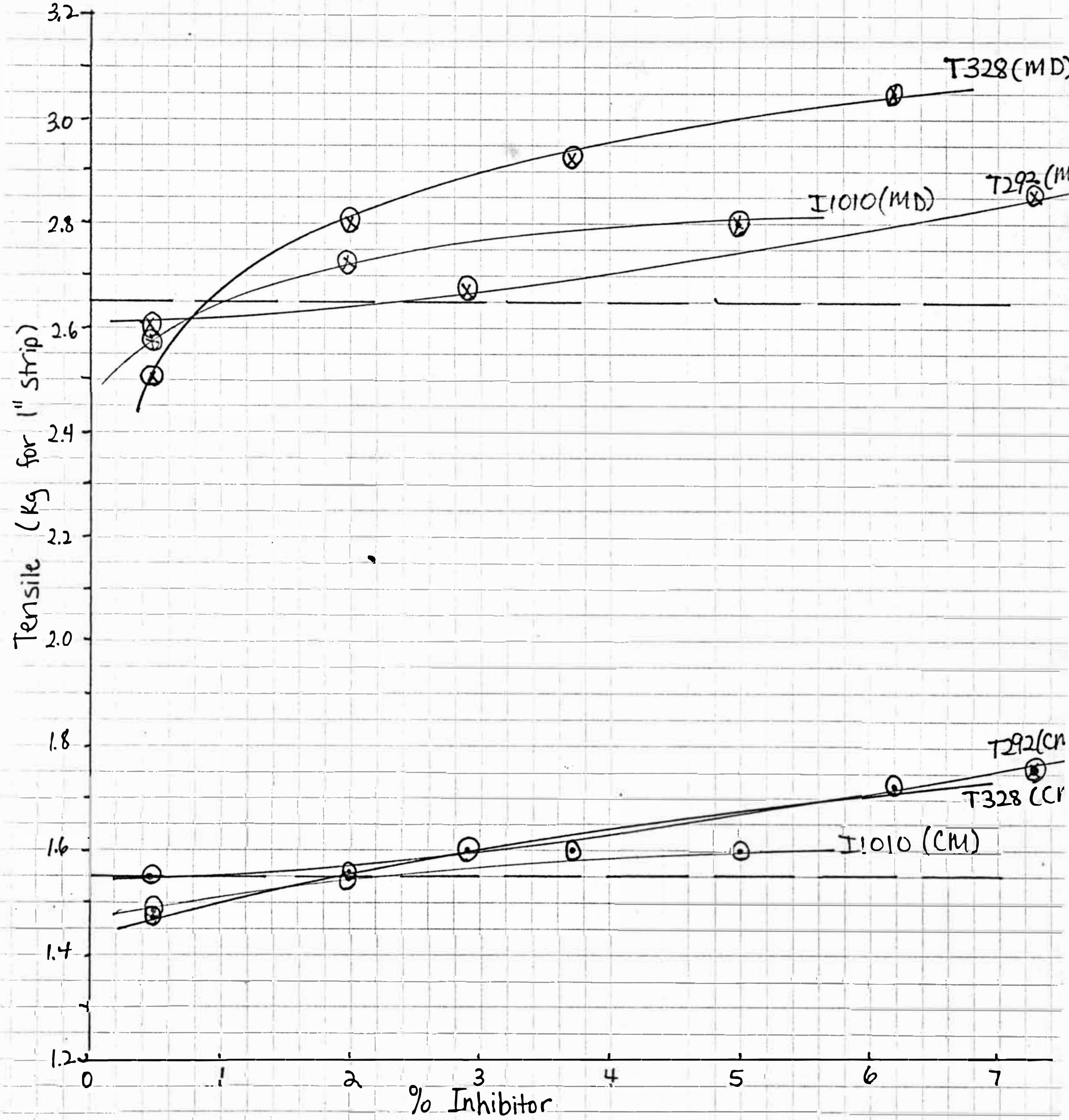


Figure 18 : Tensile Vs. % Inhibitor
(5 Mrad)

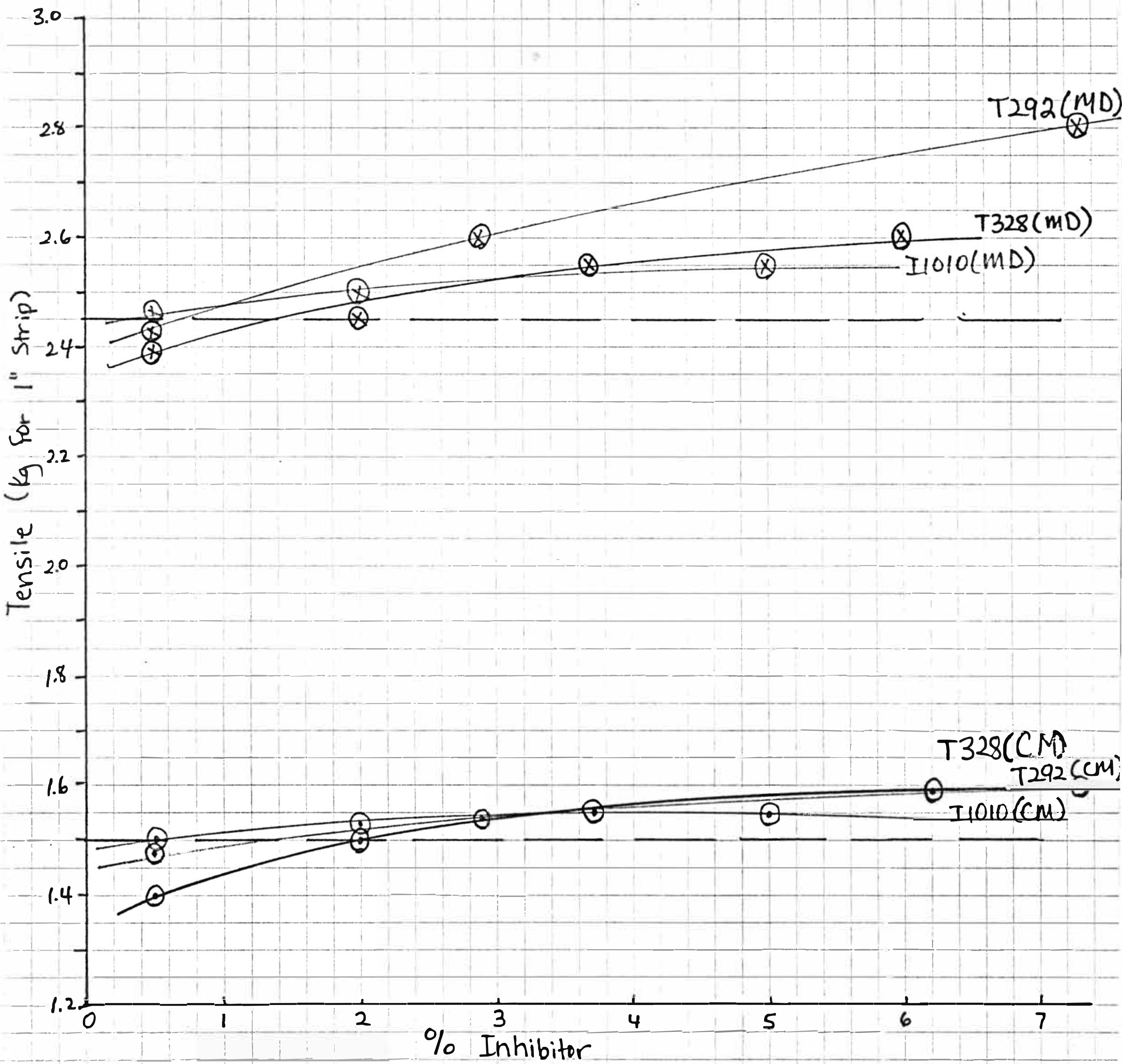


Figure 19: Tensile vs. % Inhibitor
(10 M rad)

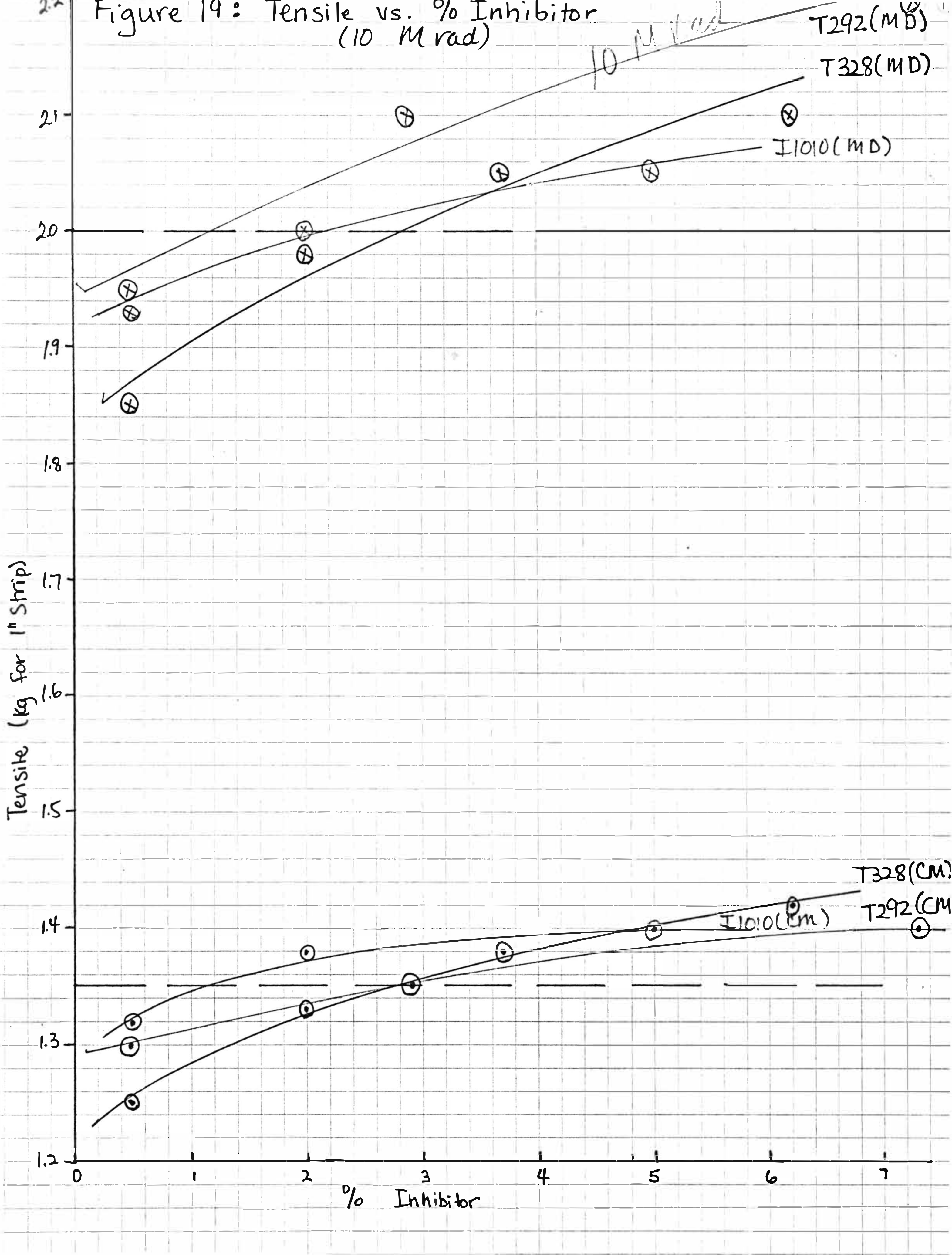


Figure 20 : Tear vs. % Inhibitor (2 M rad)

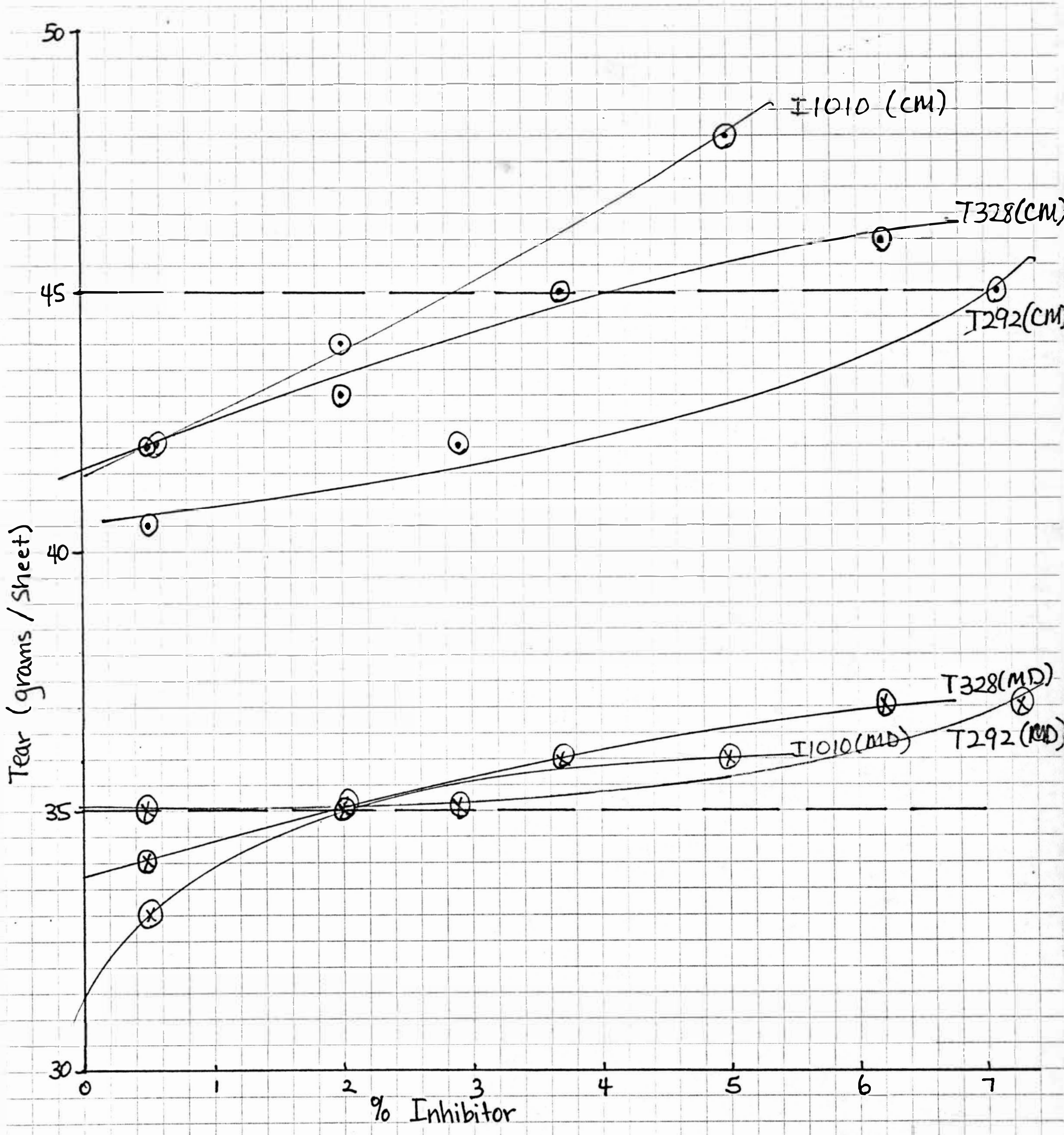


Figure 21 : Tear vs. % Inhibitor
(5 M rad)

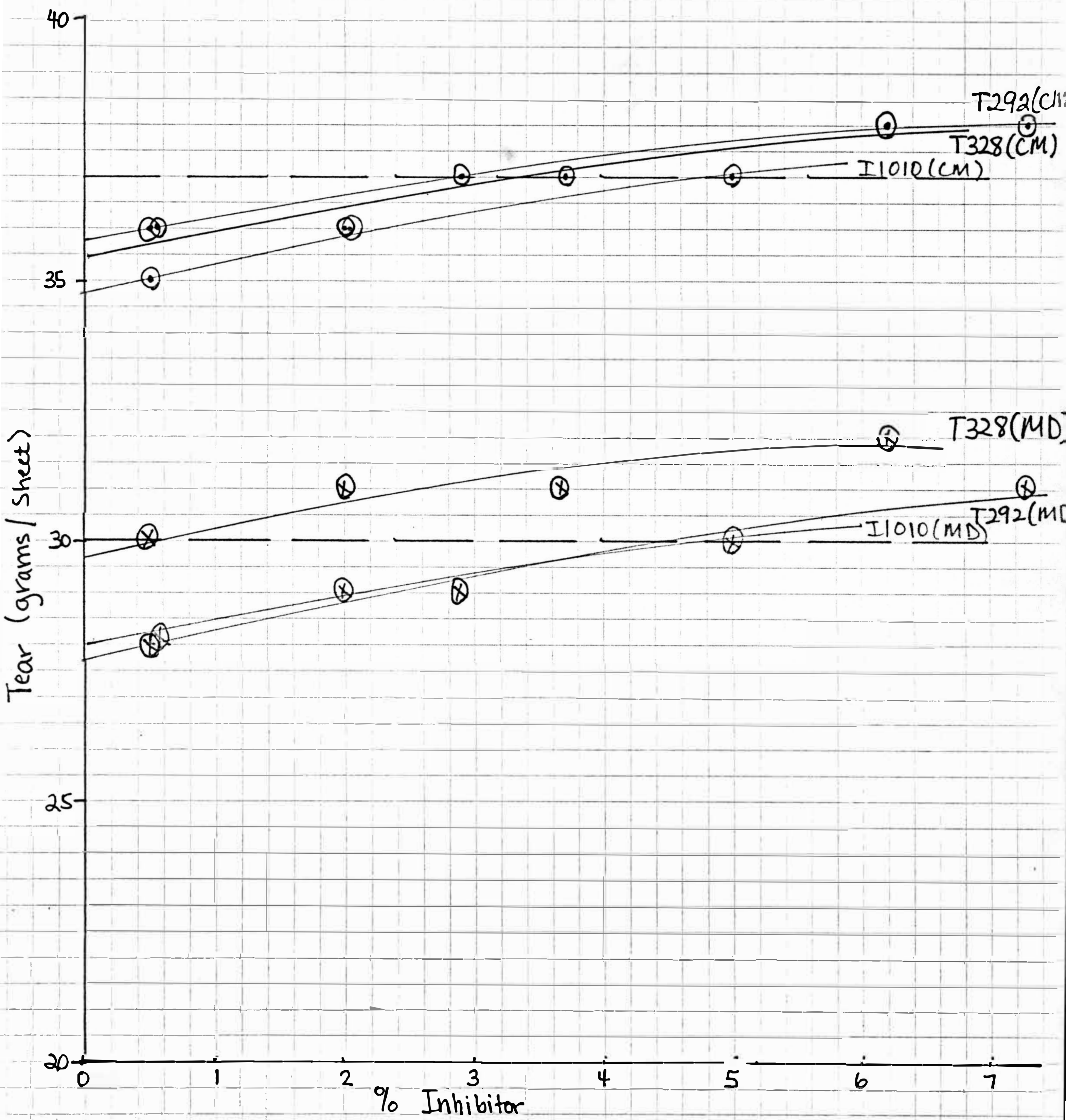


Figure 22 : Tear vs. % Inhibitor
(10 M rad)

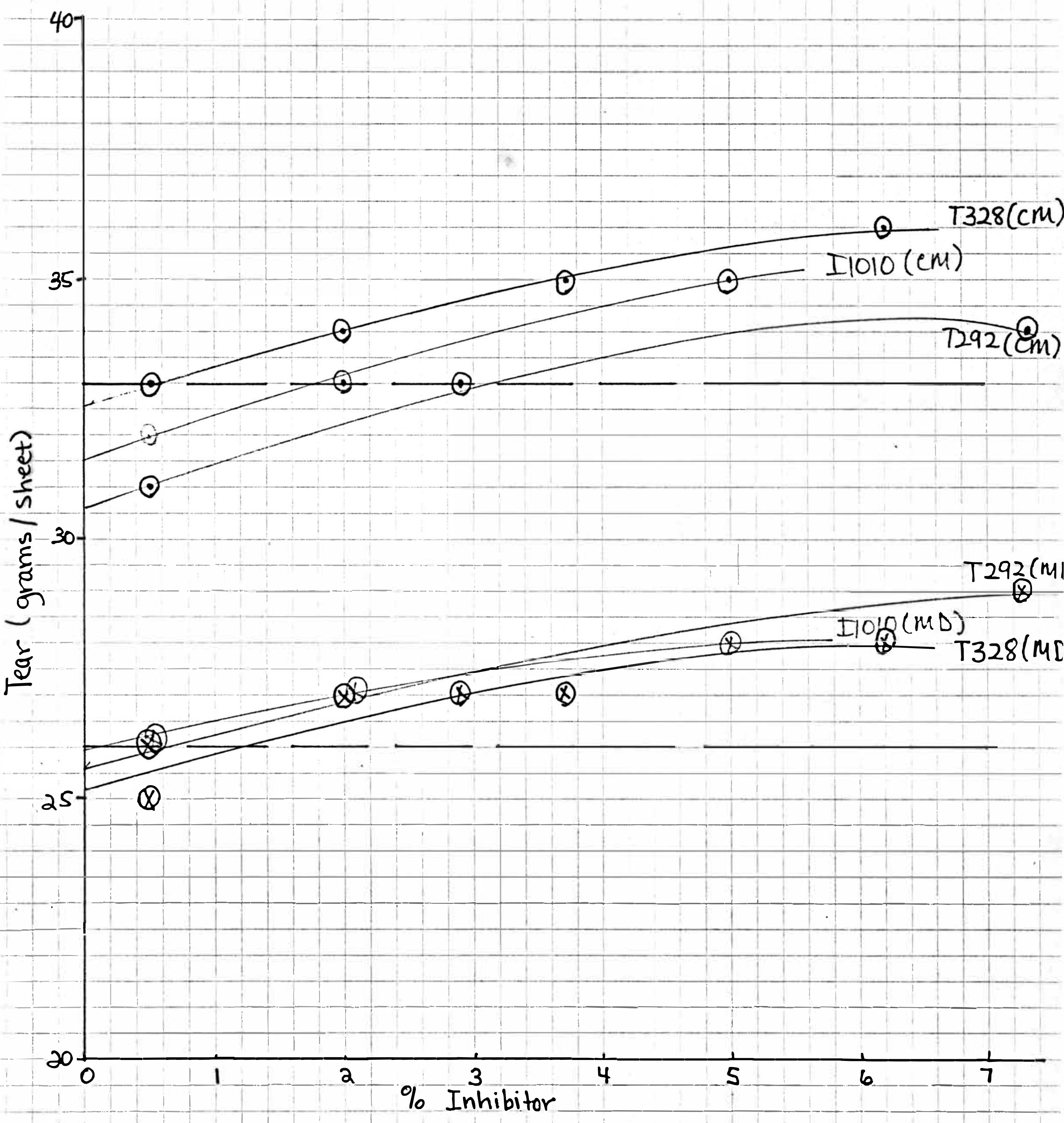


Figure 23: Burst vs. % Inhibitor
(2 Mrad)

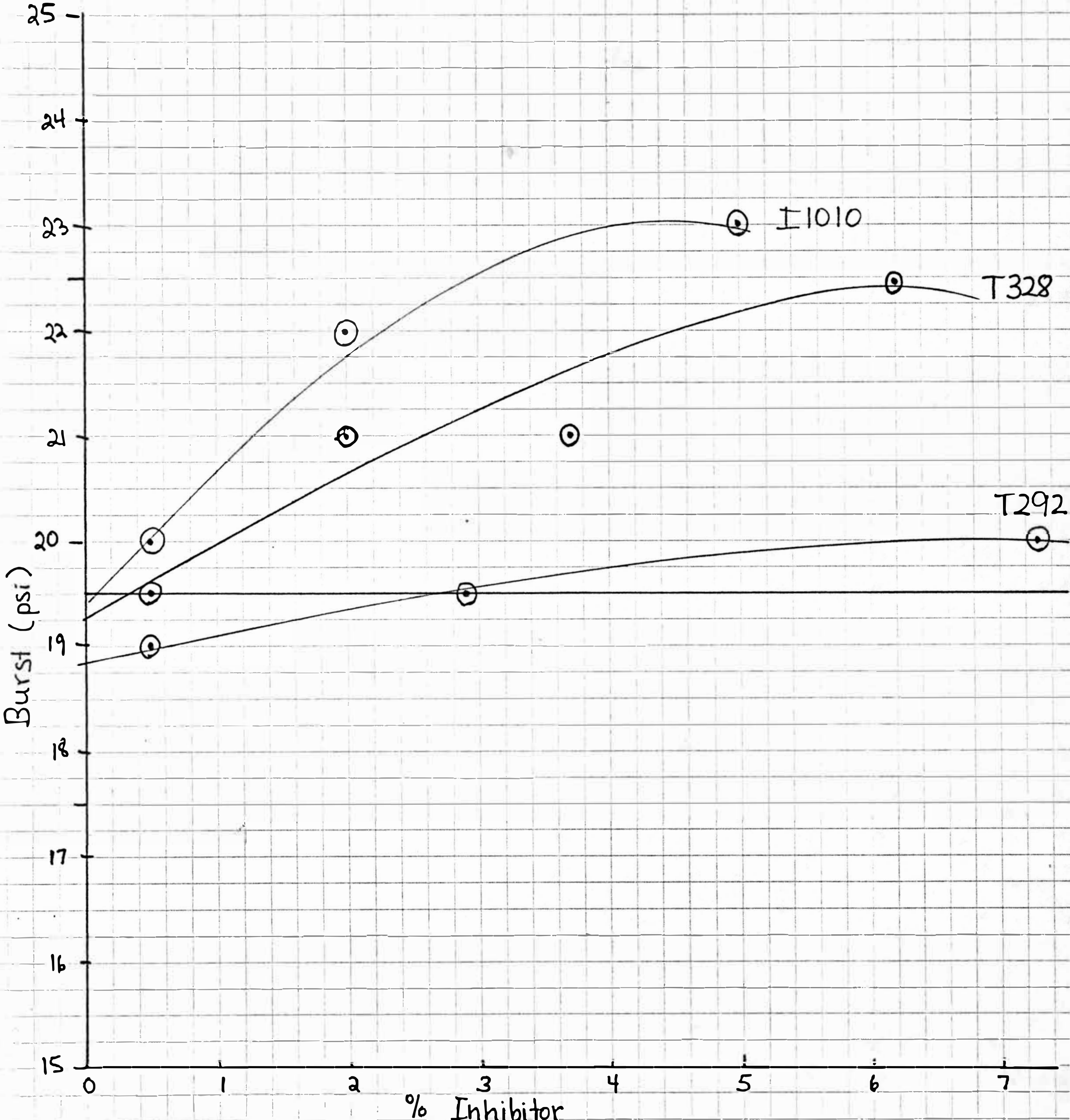
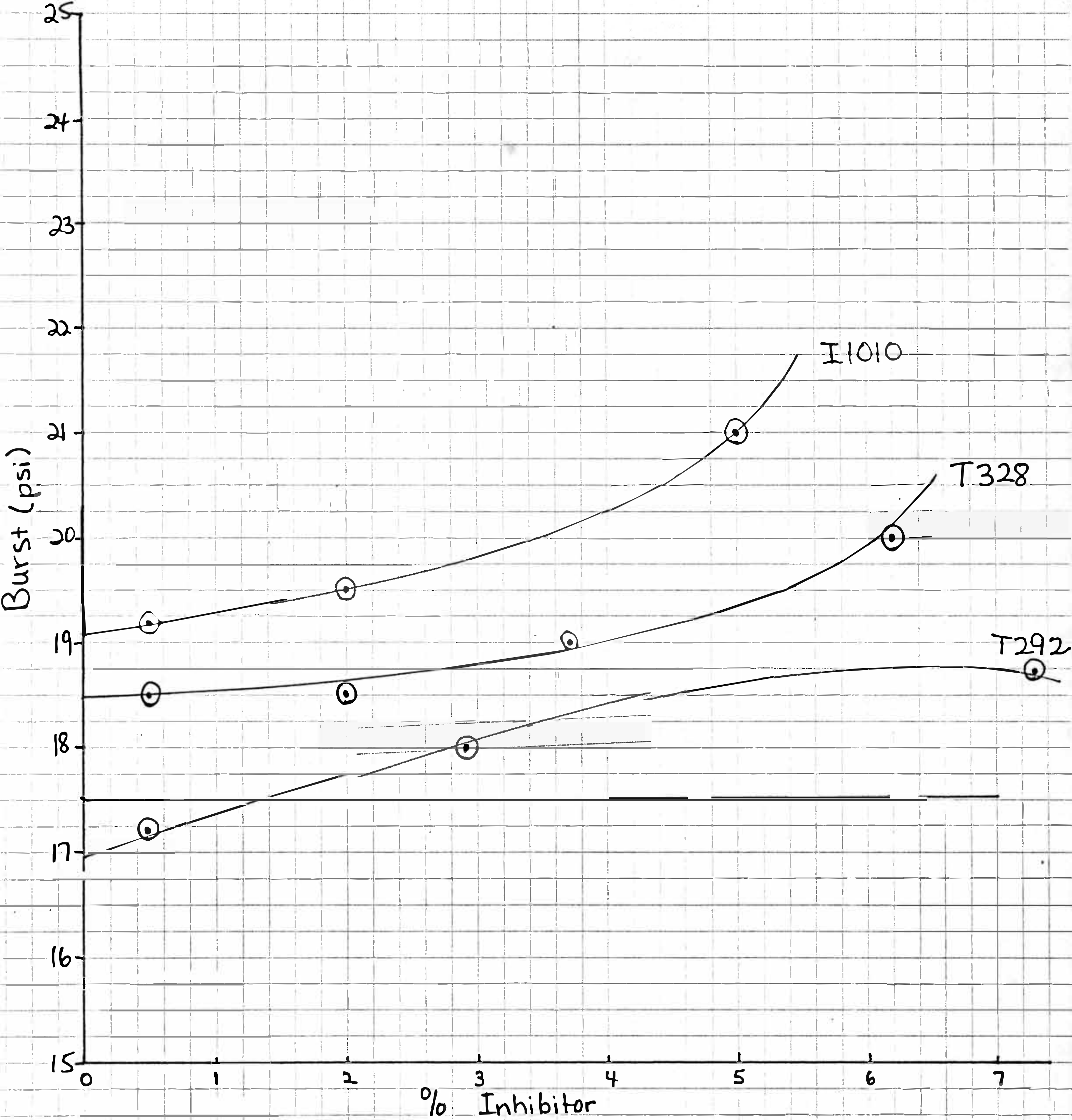


Figure 24: Burst vs. % Inhibitor
(5 M rad)



10 M Rad

Figure 25: Burst vs. % Inhibitor (10 Mrad)

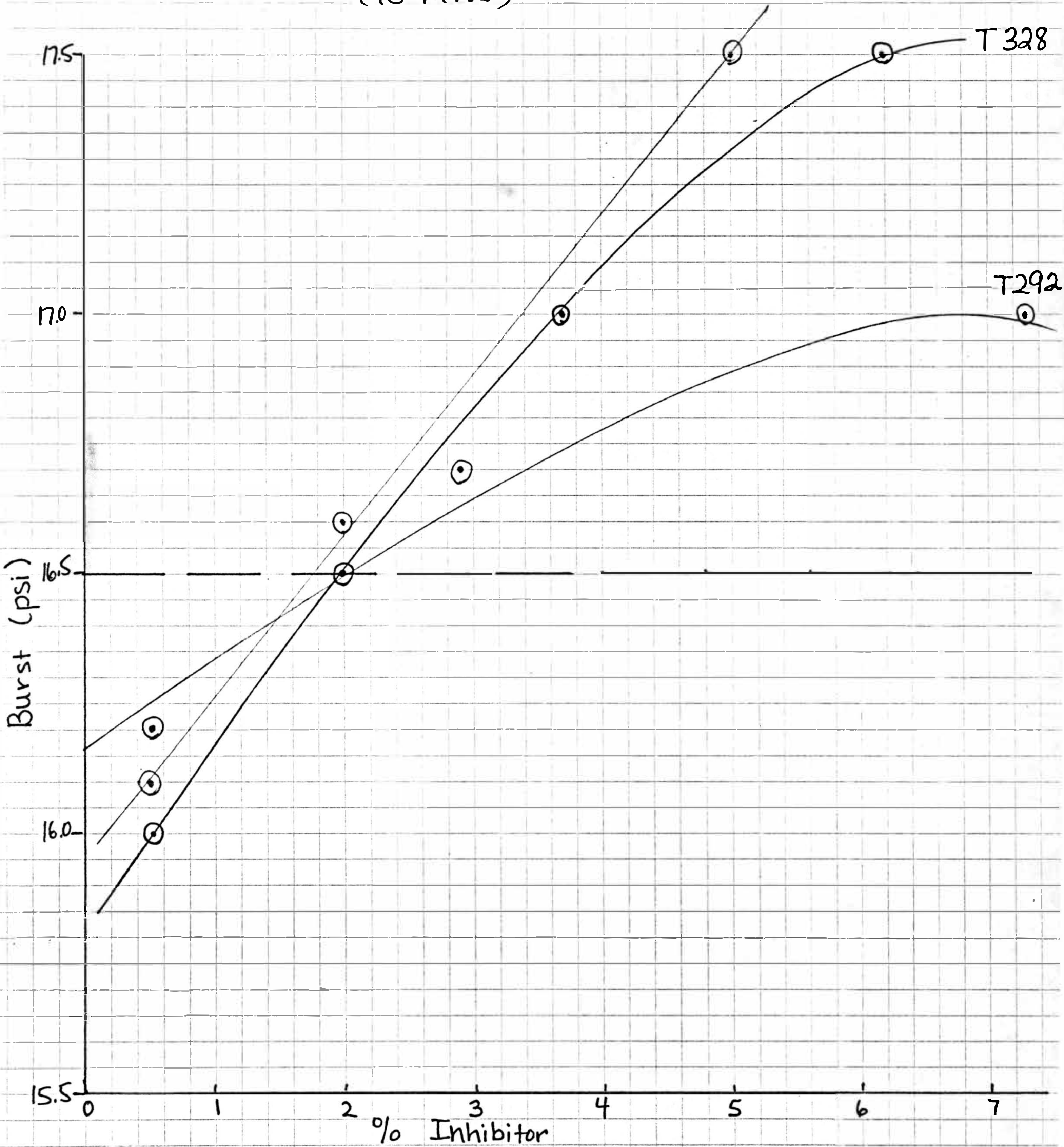


Figure 26: Folding Endurance vs. % Inhibitor
(2 M rad)

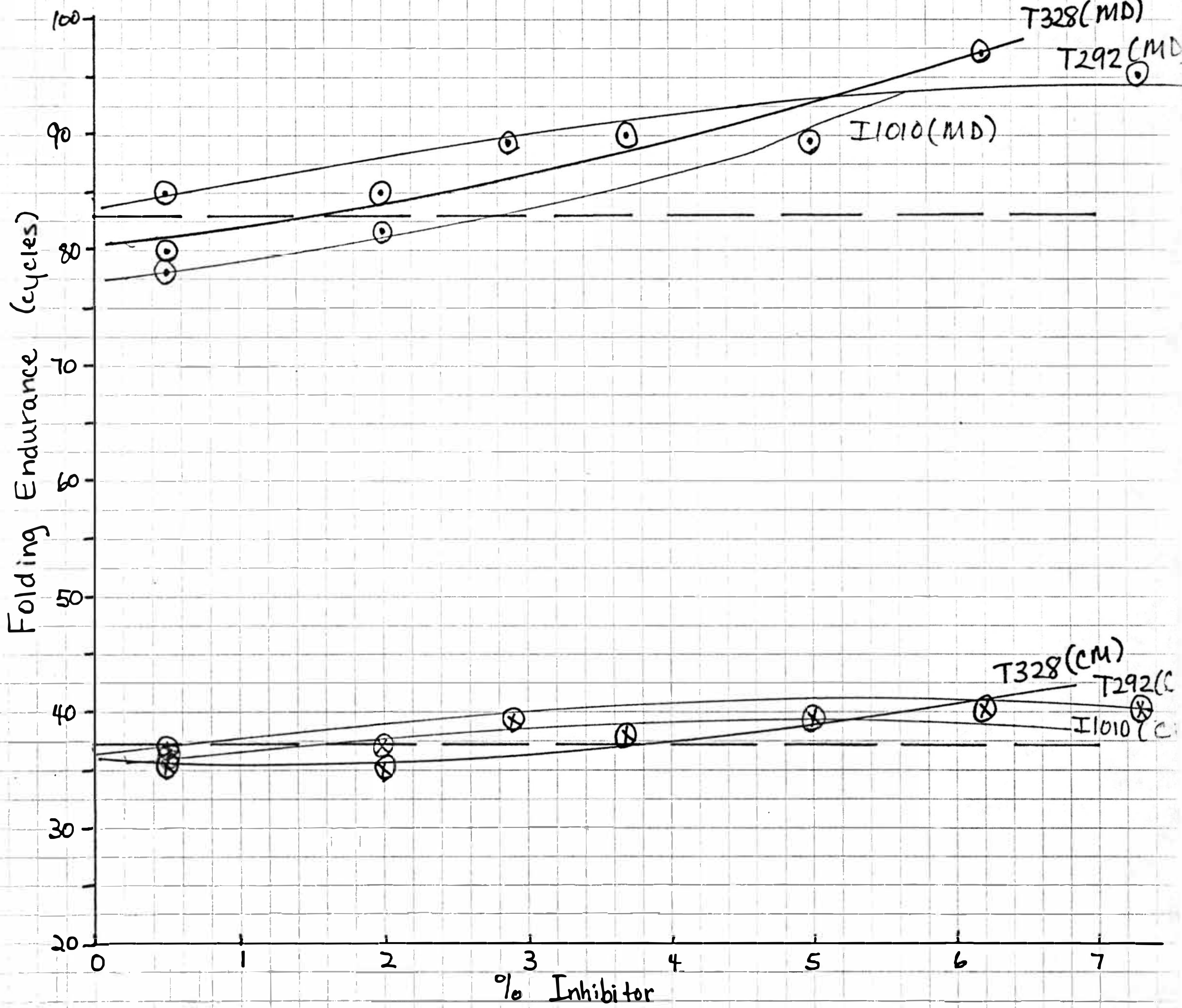
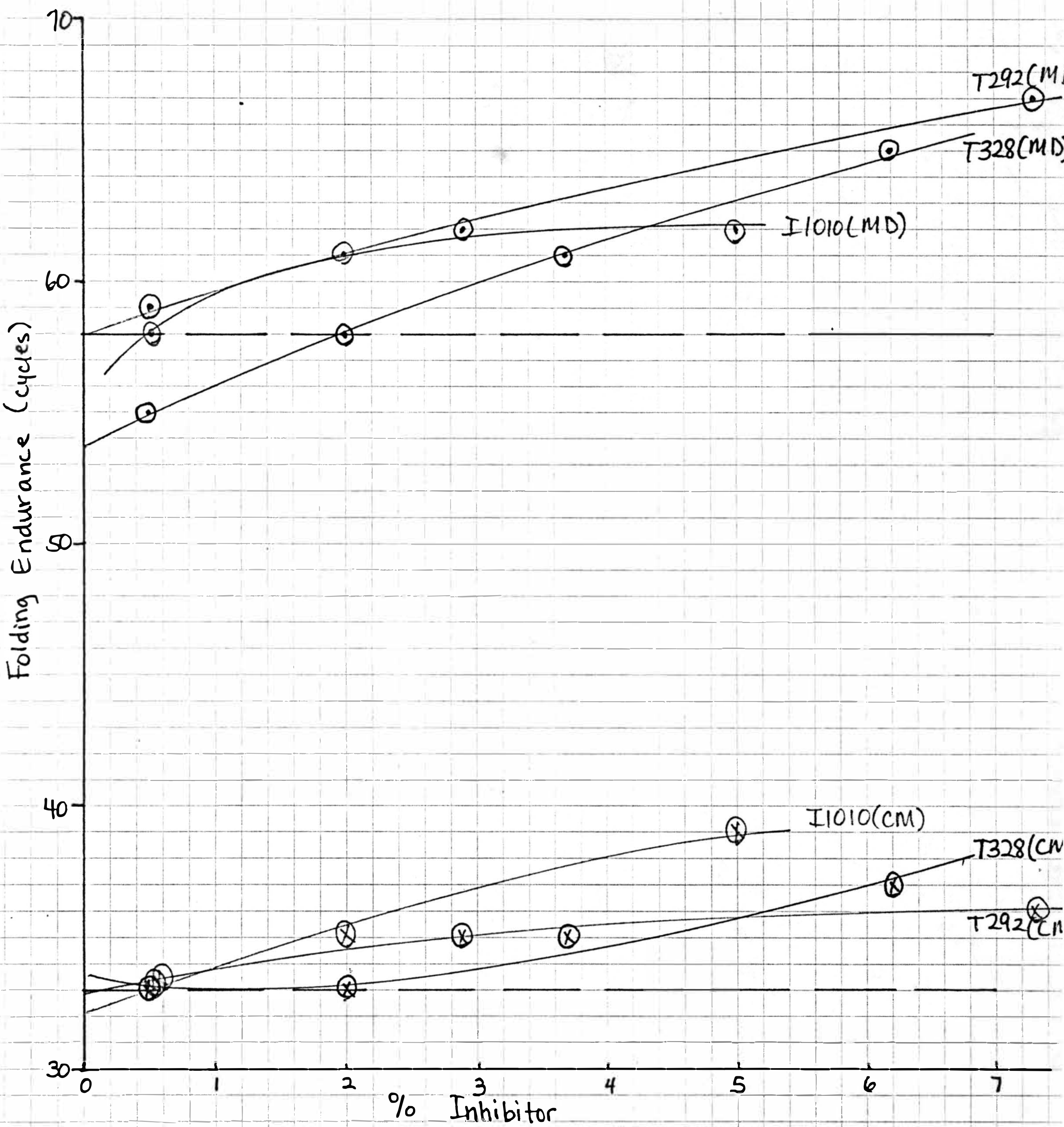


Figure 27: Folding Endurance vs. % Inhibitor (5 M rad)



10 ...

Figure 28: Folding Endurance vs. % Inhibitor
(10 M rad)

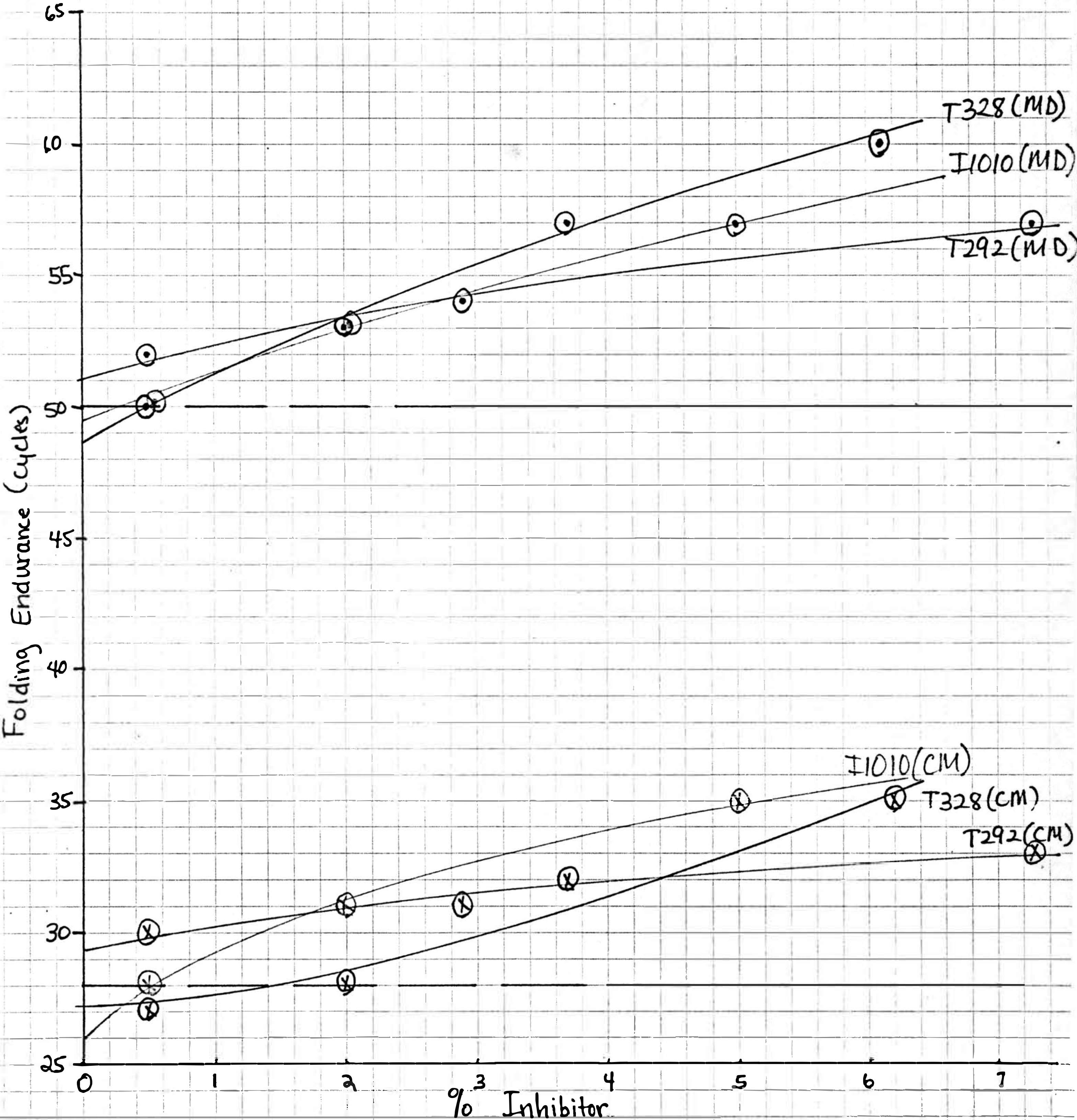


Figure 29 : B reading vs. % of T292

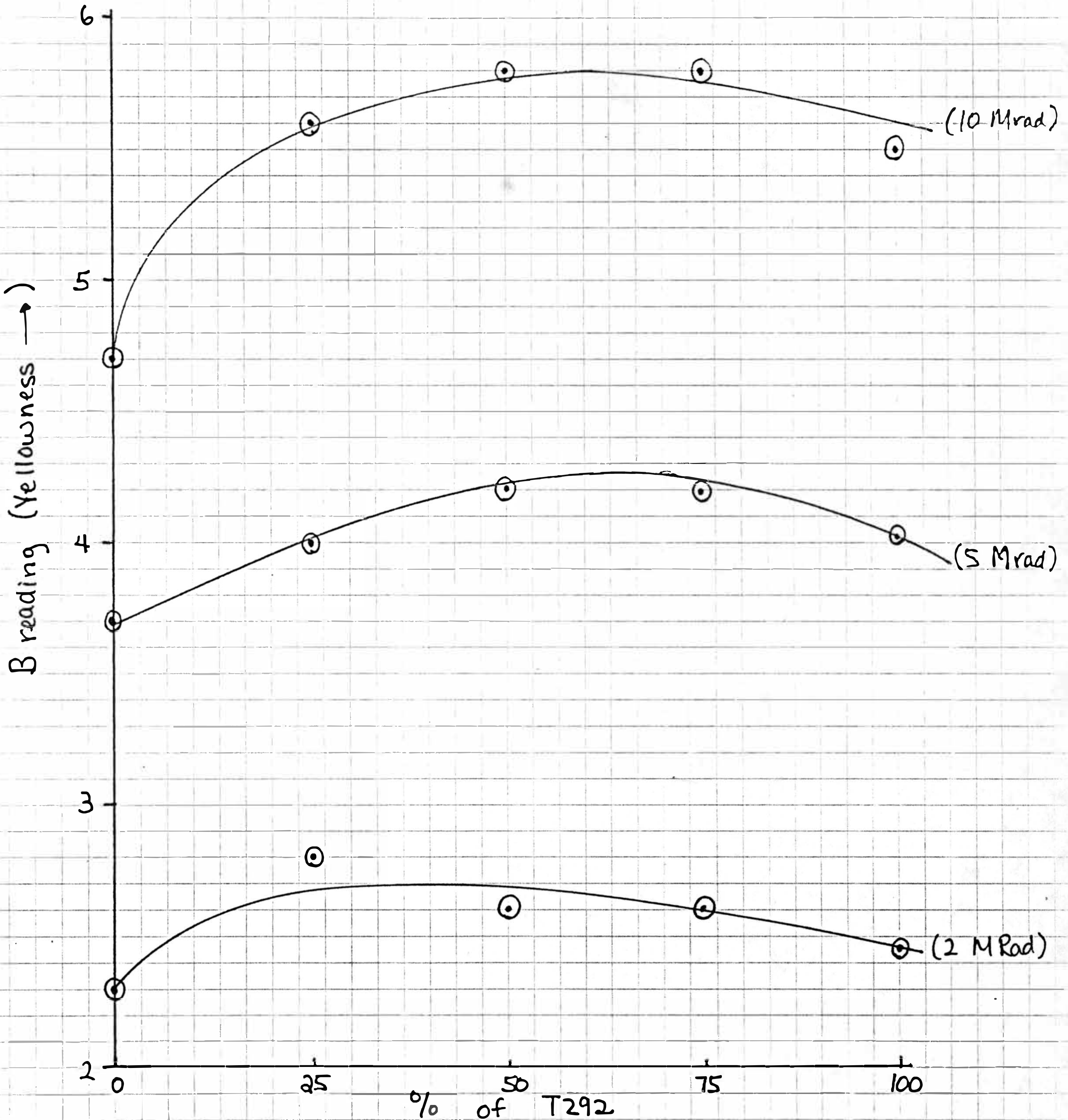


Figure 30 : Brightness vs. % of T292

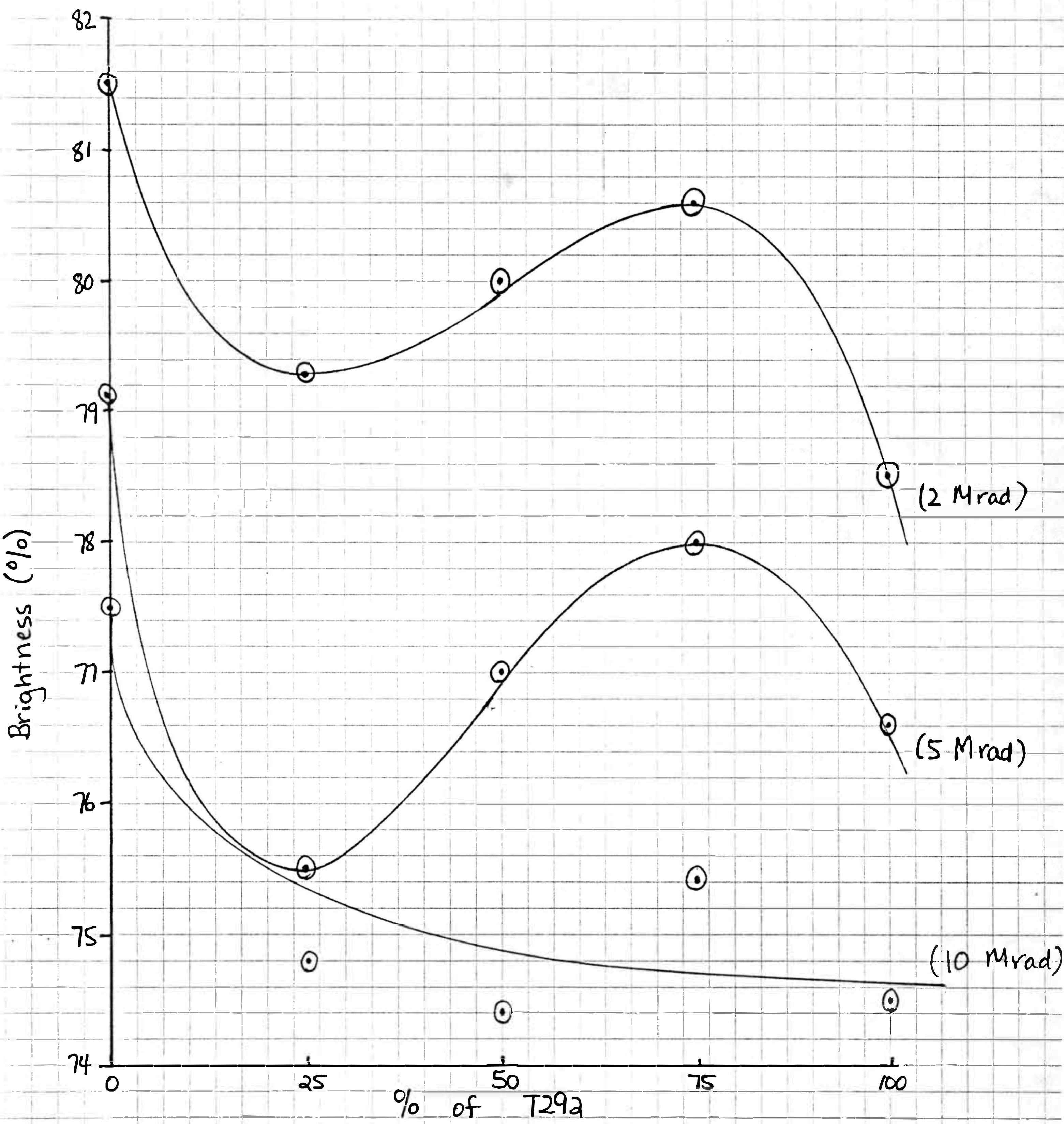


Figure 31: Tensile vs. % of T292

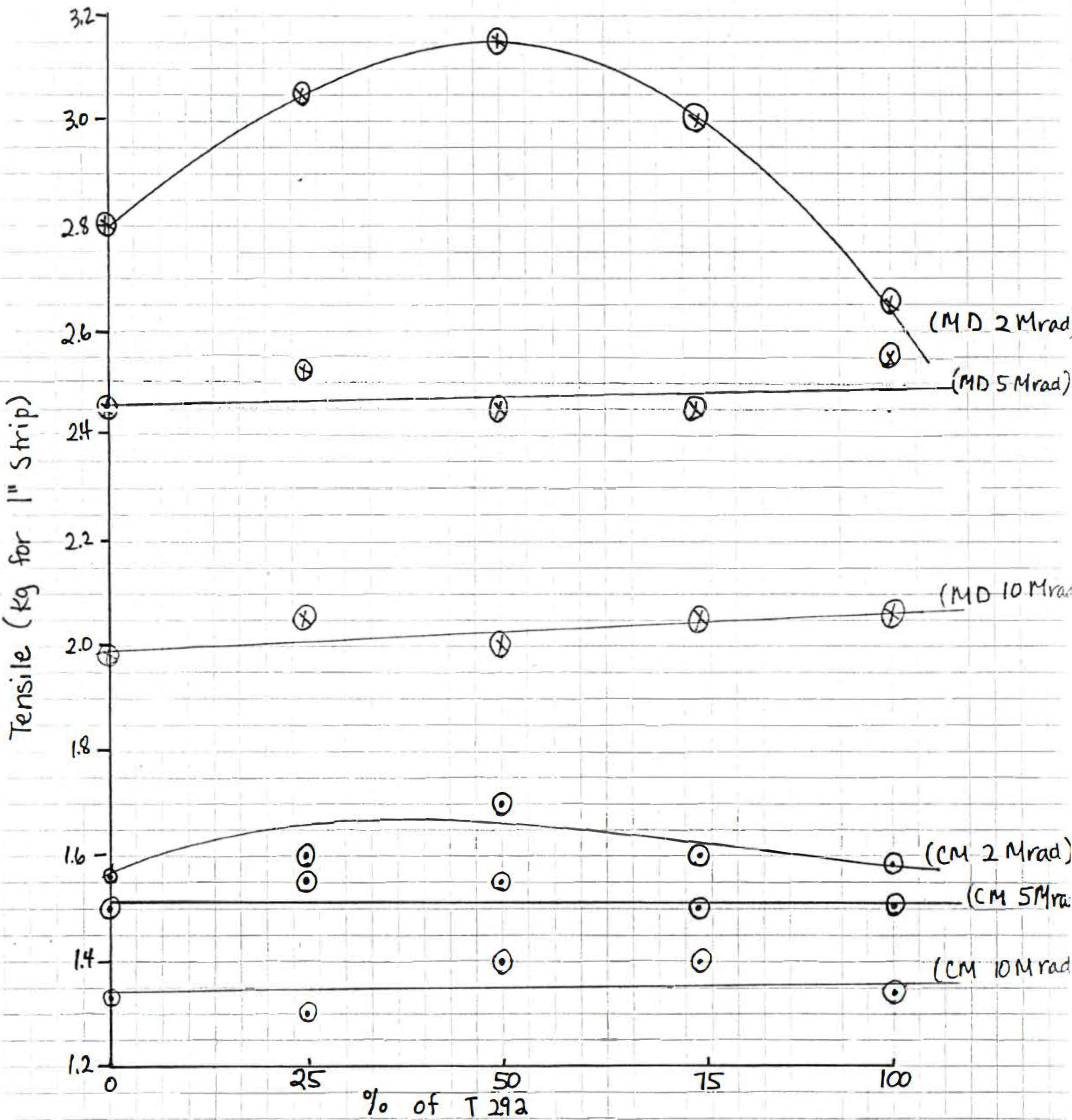


Figure 32: Tear vs. % of T292

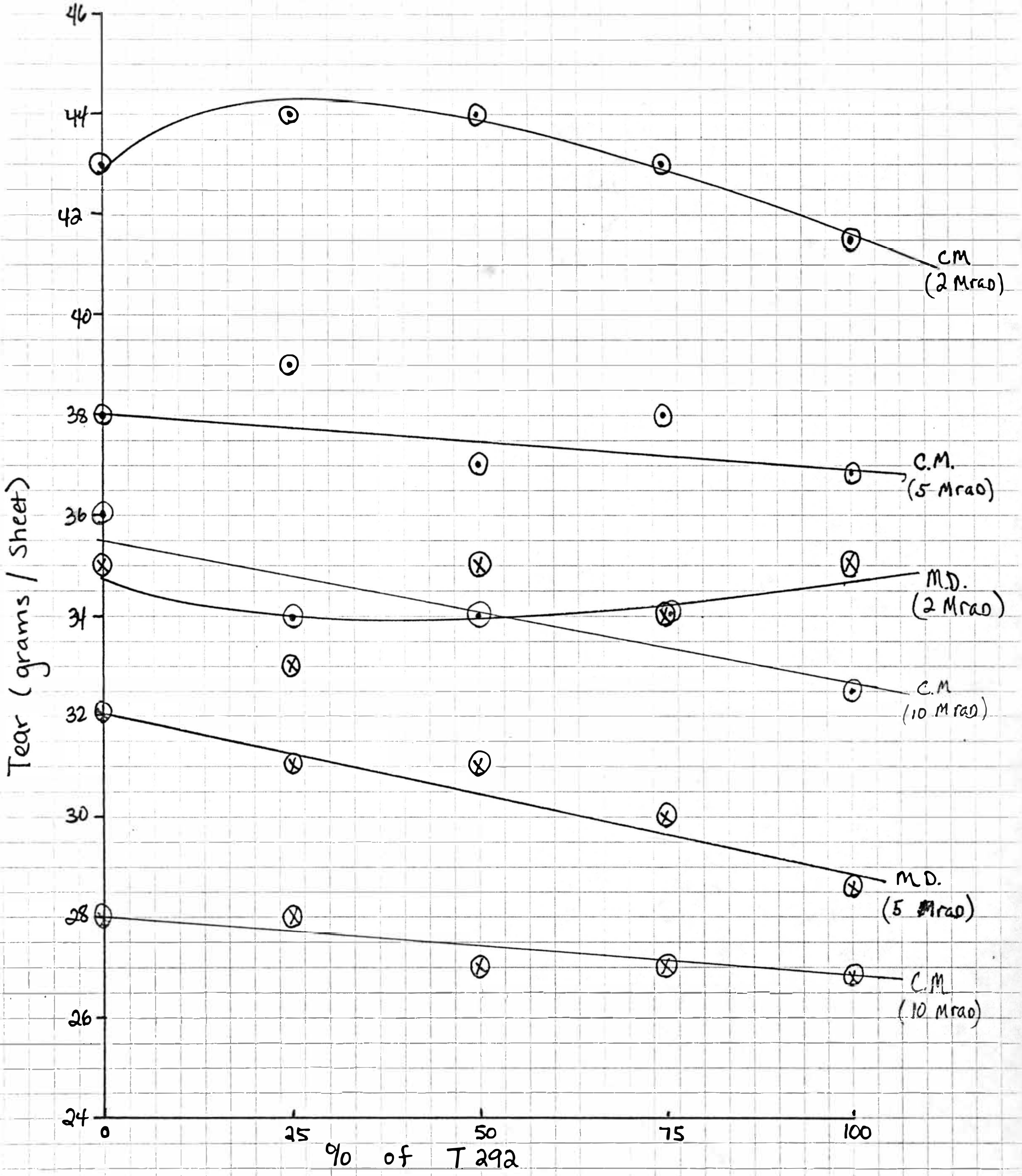


Figure 33: Burst vs. % of T292

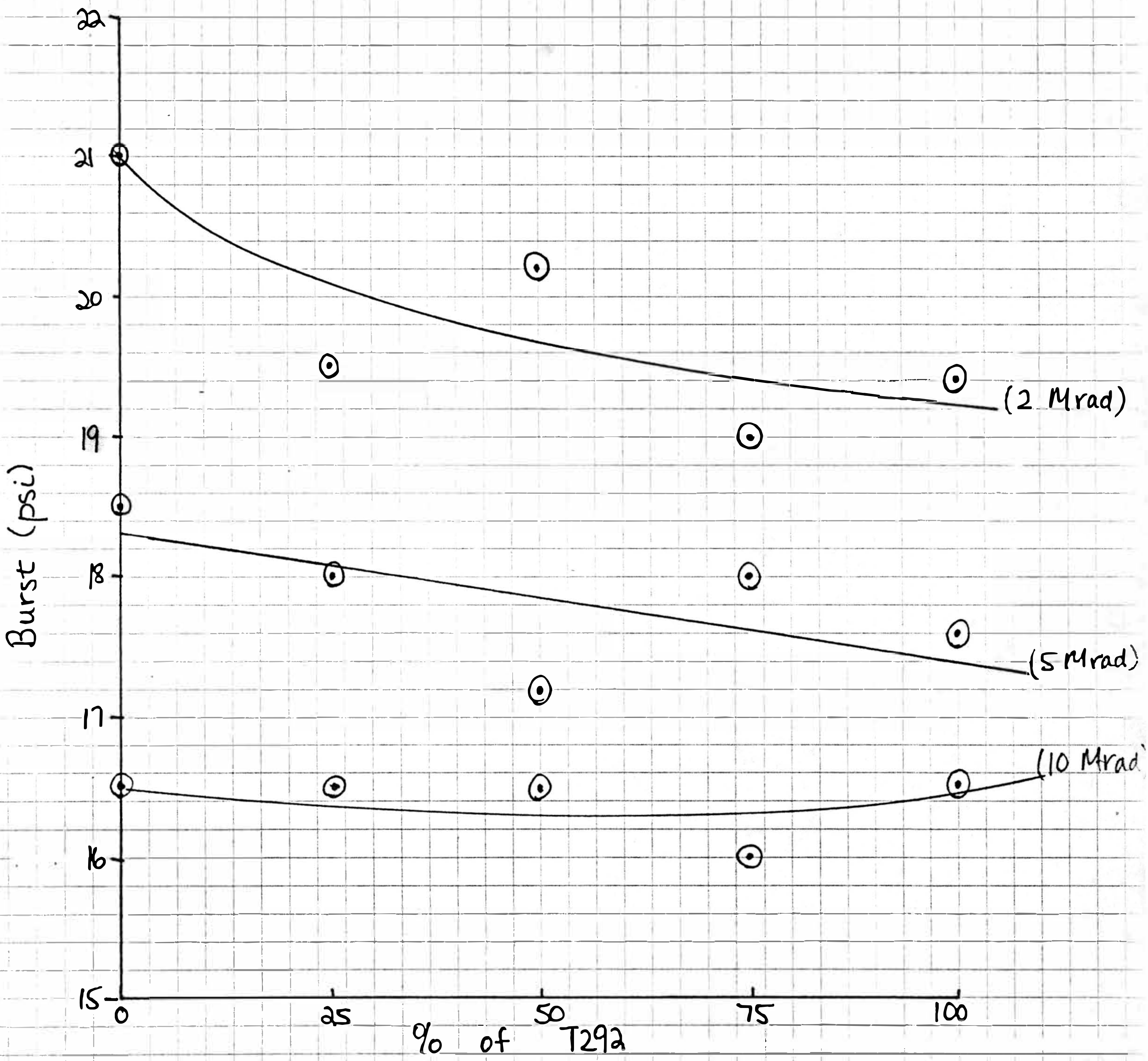
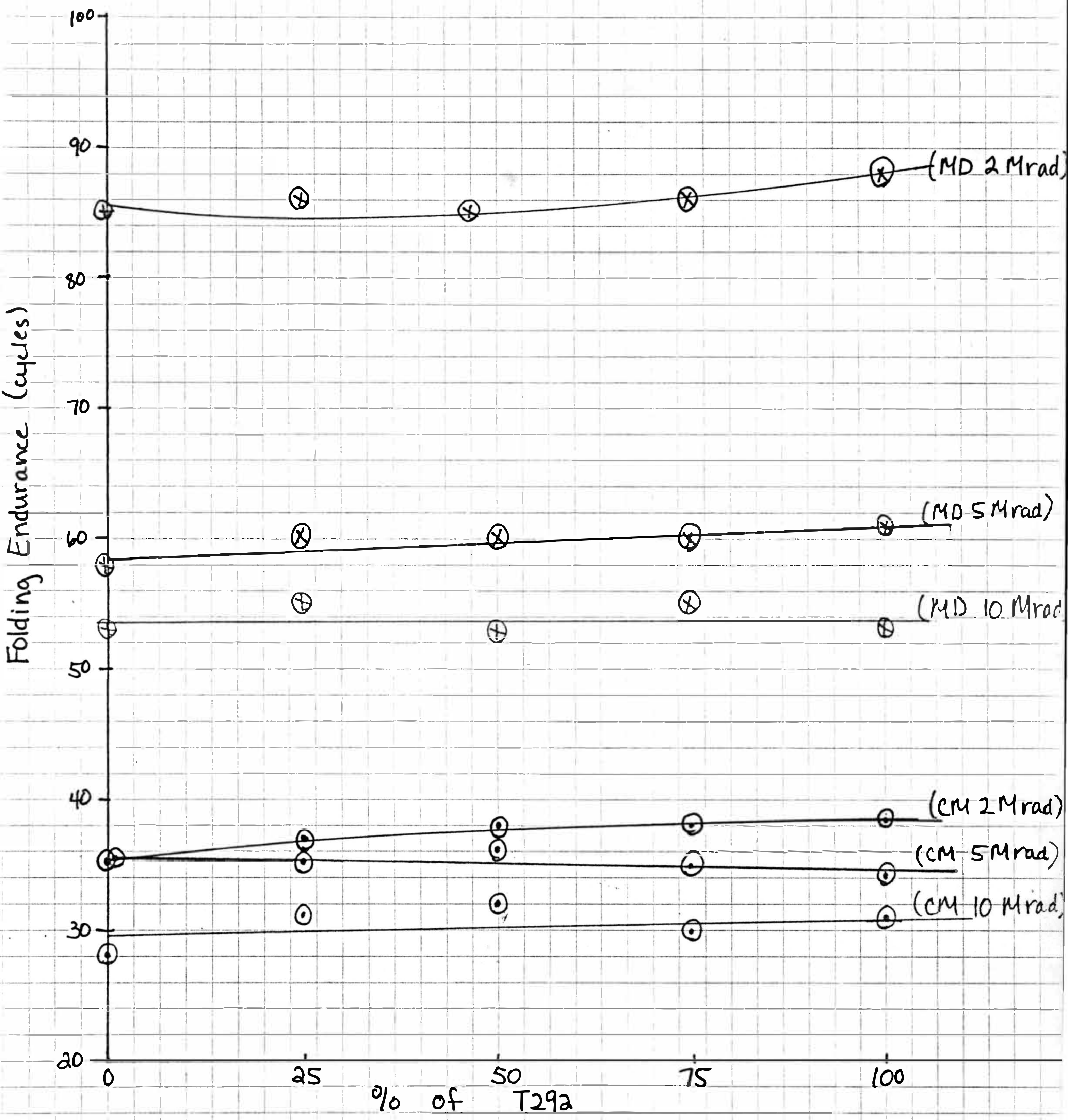


Figure 34 : Folding Endurance vs. % of T292



CONCLUSION

This investigation has shown that there is a definite damage to paper from electron beam radiation. There is a decrease in the paper properties of brightness, tensile, tear, burst, and fold; and there is an increase in the yellowness. It was also shown that the greatest percentage of damage is occurring when the sheet is first irradiated (up to 2 Mrad) as it is irradiated more the rate of damage becomes less.

This investigation has also shown that there is no general trend for an increase or decrease in legnin content to affect the properties of brightness, tensile, tear, burst, and fold as they pertain to electron beam radiation.

This investigation has also shown that the chemicals T328, T292 and I1010 from the Ciba-Geigy Corporation cause about a 10% decrease in strength at low addition levels (.5%) as compared to no addition, no effect on strength at about 2% addition, and increase the strength properties above the 2% addition level. At the higher addition levels (5-7.5%), approximately a 10-20% increase in the strength properties is observed. The chemicals were found to have a detrimental affect on brightness and yellowness. As the percentage of inhibitor was increased, the brightness decreased and the yellowness increased.

RECOMMENDATIONS

It is recommended that furhter studies be conducted to find an inexpensive and easy way to protect paper from electron beam radiation.

An investigation as to the reasons for the decrease in strength at .5% addition levels of T328, T292, and I1010 would also be of value.

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Appendices: Untreated Samples

Sample		Brightness (%) 0 Mrad	Yellowness (B-reading) 0 Mrad	Tensile (kg/1" strip) 0 Mrad (cm/md)	Tear (g/sheet) 0 Mrad (cm/md)	Burst (psi) 0 Mrad	fold (cycles) 0 Mrad (cm/md)
50 # Bag Paper	$\bar{x}$	81.1	4.8	1.75/2.55	90/72	43.2	105/330
	s	1.2	0.3	0.09/0.10	1.8/1.3	2.3	41/18.6
	n	10	5	10	6	5	10
34# Castex waterleaf	$\bar{x}$	83.9	1.5	1.60/2.85	48/40	23.0	41/115
	s	1.0	0.1	0.11/0.13	1.1/2.0	1.3	8.3/12.5
	n	10	5	10	6	5	10
Cotton	$\bar{x}$	80.5	Not tested	2.30	57	11.5	342
	s	0.9		0.08	1.5	1.2	21.6
	n	10		10	6	5	10
Bleached S.W.	$\bar{x}$	70.5	Not Tested	3.20	64	40.3	235
	s	0.8		0.12	2.3	2.1	33.2
	n	10		10	6	5	10
Unbleached S.W.	$\bar{x}$	21.2	Not tested	3.30	67	37.1	487
	s	2.3		0.11	2.1	1.7	48.3
	n	10		10	6	5	10
Groundwood	$\bar{x}$	50.5	Not Tested	1.29	33	9.2	87
	s	1.3		0.13	1.8	0.8	18.7
	n	10		10	6	5	10

Tear (grams/sheet)

Sample		Dose of Electron Beam					
		2 Mrad		5 Mrad		10 Mrad	
		CM	MD	CM	MD	CM	MD
50# Bag	$\bar{x}$	77	64	64	56	51	44
	s	6.3	3.8	2.6	7.6	5.4	3.1
	n	6	6	6	6	6	6
34# Waterleaf	$\bar{x}$	45	35	37	30	33	26
	s	0.6	2.0	1.6	2.1	3.4	2.6
	n	6	6	6	6	6	6
6.2% T328	$\bar{x}$	46	37	38	32	36	28
	s	1.1	0.5	1.2	0.8	1.1	1.1
	n	6	6	6	6	6	6
3.7% T328	$\bar{x}$	45	36	37	31	35	27
	s	1.2	0.1	1.3	0.7	1.3	0.8
	n	6	6	6	6	6	6
20% T328	$\bar{x}$	43	35	36	31	34	27
	s	0.9	0.3	0.9	0.6	0.9	0.3
	N	6	6	6	6	6	6
0.5% T328	$\bar{x}$	42	34	36	3[illegible]	33	25
	s	1.3	1.1	1.3	0.7	1.6	0.5
	n	6	6	6	6	6	6
7.3% T292	$\bar{x}$	45	37	38	31	34	29
	s	0.7	0.2	0.8	1.[illegible]	0.6	0.5
	n	6	6	6	6	6	6
2.9% T292	$\bar{x}$	42	35	37	29	33	27
	s	0.6	1.3	1.3	1.1	0.8	1.0
	n	6	6	6	6	6	6
0.5% T292	$\bar{x}$	40	35	36	28	31	26
	s	1.2	0.8	1.2	0.6	1.8	1.1
	n	6	6	6	6	6	6
5.0% I1010	$\bar{x}$	48	36	37	30	35	28
	s	1.1	0.9	1.6	0.8	0.6	1.2
	n	6	6	6	6	6	6
2.0% I1010	$\bar{x}$	44	35	36	29	33	29
	s	1.3	1.1	0.9	0.5	1.2	1.2
	n	6	6	6	6	6	6
0.5% I1010	$\bar{x}$	42	33	35	28	32	26
	s	1.8	0.6	0.5	1.7	0.2	1.5
	n	6	6	6	6	6	6
2.0% 25/75 T292/T328	$\bar{x}$	43	34	38	30	34	27
	s	2.1	1.2	1.3	1.5	0.9	1.8
	n	6	6	6	6	6	6
2.0% 50/50 T292/T328	$\bar{x}$	44	35	37	31	34	27
	s	0.8	1.1	1.3	1.3	0.6	1.1
	n	6	6	6	6	6	6
2.0% 75/25 T292/T328	$\bar{x}$	44	33	39	31	34	28
	s	0.3	0.9	1.1	1.8	0.9	1.2
	n	6	6	6	6	6	6

Tensile (kg / 1" strip)

Sample		Dose of Electron Beam					
		2 Mrad		5 mRad		10 Mrad	
		CM	MD	CM	MD	CM	MD
50# Bag	$\bar{x}$	1.65	2.50	1.55	2.25	1.50	2.10
	s	.15	.17	.18	.23	.15	.21
	n	10	10	10	10	10	10
34# Waterleaf	$\bar{x}$	1.55	2.65	1.50	2.45	1.35	2.00
	s	.15	.23	.17	.21	.14	.21
	n	10	10	10	10	10	10
6.2% T328	$\bar{x}$	1.72	3.05	1.58	2.60	1.42	2.10
	s	.17	.21	.13	.20	.15	.23
	n	10	10	10	10	10	10
3.7% T328	$\bar{x}$	1.60	2.92	1.55	2.55	1.38	2.05
	s	.16	.15	.17	.14	.12	.20
	n	10	10	10	10	10	10
2.0% T328	$\bar{x}$	1.56	2.80	1.50	2.45	1.33	1.98
	s	.12	.19	.14	.14	.10	.17
	n	10	10	10	10	10	10
0.5% T328	$\bar{x}$	1.47	2.50	1.40	2.38	1.25	1.85
	s	.11	.16	.17	.15	.11	.13
	n	10	10	10	10	10	10
7.3% T292	$\bar{x}$	1.76	2.85	1.60	2.80	1.40	2.20
	s	.18	.21	.20	.20	.16	.16
	n	10	10	10	10	10	10
2.9% T292	$\bar{x}$	1.60	2.68	1.52	2.60	1.35	2.10
	s	.15	.19	.18	.13	.14	.15
	n	10	10	10	10	10	10
0.5% T292	$\bar{x}$	1.55	2.60	1.47	2.42	1.30	1.95
	s	.17	.17	.14	.12	.16	.10
	n	10	10	10	10	10	10
5.0% I 1010	$\bar{x}$	1.60	2.80	1.55	2.55	1.40	2.05
	s	.19	.21	.15	.10	.12	.11
	n	10	10	10	10	10	10
2.0% I 1010	$\bar{x}$	1.55	2.72	1.52	2.50	1.38	2.00
	s	.18	.18	.19	1.6	.10	.15
	n	10	10	10	10	10	10
0.5% I 1010	$\bar{x}$	1.48	2.58	1.50	2.46	1.32	1.93
	s	.18	.18	.17		.11	.16
	n	10	10	10	10	10	10
20% 25/75 T292/T328	$\bar{x}$	1.60	3.00	1.50	2.45	1.40	2.05
	s	.16	.17	.20	.23	.21	.18
	n	10	10	10	10	10	10
20% 50/50 T292/T328	$\bar{x}$	1.70	3.15	1.55	2.45	1.40	2.00
	s	.17	.19	.20	.22	.17	.21
	n	10	10	10	10	10	10
20% 75/25 T292/T328	$\bar{x}$	1.60	3.05	1.55	2.52	1.30	2.05
	s	.21	.24	.18	.21	.22	.25
	n	10	10	10	10	10	10

Folding Endurance (cycles)

Sample		Dose of Electron Beam					
		2 Mrad		5 Mrad		10 Mrad	
		CM	MD	CM	MD	CM	MD
50# Bag	$\bar{x}$	87	272	72	230	68	202
	s	13	53	18	37	22	42
	n	10	10	10	10	10	10
34# Waterleaf	$\bar{x}$	37	83	33	58	28	50
	s	5.1	12.2	7.2	6.5	11.0	10.7
	n	10	10	10	10	10	10
6.2% T328	$\bar{x}$	40	97	37	65	35	60
	s	4.2	25.3	8.3	7.5	6.3	6.5
	n	10	10	10	10	10	10
3.7% T328	$\bar{x}$	38	90	35	61	32	57
	s	3.0	18.1	5.4	3.6	7.8	7.3
	n	10	10	10	10	10	10
2.0% T328	$\bar{x}$	35	85	33	58	28	53
	s	5.2	16.0	7.3	4.9	12.1	12.2
	n	10	10	10	10	10	10
0.5% T328	$\bar{x}$	35	80	33	55	27	50
	s	4.1	17.3	6.7	3.5	3.6	4.8
	n	10	10	10	10	10	10
7.3% T292	$\bar{x}$	40	95	36	67	33	57
	s	3.7	10.0	12.6	7.2	5.4	13.5
	n	10	10	10	10	10	10
2.9% T292	$\bar{x}$	39	89	35	62	31	54
	s	3.6	5.9	13.5	3.1	6.7	6.7
	n	10	10	10	10	10	10
0.5% T292	$\bar{x}$	37	85	33	59	30	52
	s	5.7	7.3	12.1	8.9	8.1	8.3
	n	10	10	10	10	10	10
5.0% I1010	$\bar{x}$	39	89	38	62	35	57
	s	5.9	12.1	10.1	10.1	7.2	5.1
	n	10	10	10	10	10	10
2.0% I1010	$\bar{x}$	37	82	35	61	31	53
	s	6.3	6.7	7.2	12.1	3.7	2.0
	n	10	10	10	10	10	10
0.5% I1010	$\bar{x}$	36	78	33	58	28	50
	s	3.4	3.0	5.6	3.5	4.6	6.7
	n	10	10	10	10	10	10
2.0% 25/75 T292/T328	$\bar{x}$	38	86	35	60	30	55
	s	6.2	13.1	10.1	12.6	13.7	11.5
	n	10	10	10	10	10	10
20% 50/50 T292/T328	$\bar{x}$	38	85	36	60	32	53
	s	5.4	10.2	11.4	16.3	17.1	10.2
	n	10	10	10	10	10	10
20% 75/25 T292/T328	$\bar{x}$	37	86	35	60	31	55
	s	5.9	5.9	7.0	11.0	5.4	10.3
	n	10	10	10	10	10	10

Sample		Dose of Electron Beam								
		Brightness (%)			Yellowness (B-reading)			Burst (psi)		
		2 Mrad	5 Mrad	10 Mrad	2 Mrad	5 Mrad	10 Mrad	2 Mrad	5 Mrad	10 Mrad
50# Bag Paper	$\bar{x}$	79.5	77.5	77.0	5.0	5.3	5.6	38	34	27
	s	0.5	0.7	0.9	0.1	0.1	0.2	2.1	2.3	1.7
	n	10	10	10	5	5	5	5	5	5
34# Waterleaf	$\bar{x}$	82.1	80.1	79.1	2.0	3.3	4.0	19.5	17.5	16.5
	s	2.1	0.9	1.3	0.1	0.2	0.1	1.6	1.5	2.1
	n	10	10	10	5	5	5	5	5	5
6.2% T328	$\bar{x}$	78.7	76.2	73.8	3.1	4.3	5.8	22.4	20.0	17.5
	s	0.6	2.1	1.0	0.3	0.1	0.2	1.8	2.1	3.5
	n	10	10	10	5	5	5	5	5	5
3.7% T328	$\bar{x}$	79.5	78.0	75.5	2.7	4.0	5.5	21.0	19.0	17.0
	s	1.2	0.6	1.1	0.3	0.5	0.1	1.1	1.5	2.1
	n	10	10	10	5	5	5	5	5	5
2.0% T328	$\bar{x}$	81.5	79.1	77.5	2.3	3.7	4.7	21.0	18.5	16.5
	s	1.8	0.8	0.7	0.1	0.3	0.2	1.0	0.5	1.2
	n	10	10	10	5	5	5	5	5	5
0.5% T328	$\bar{x}$	82.1	80.0	79.1	2.1	3.4	4.3	19.5	18.5	16.0
	s	0.6	0.7	0.5	0.1	0.1	0.2	1.6	1.7	2.1
	n	10	10	10	5	5	5	5	5	5
7.3% T292	$\bar{x}$	75.0	74.0	72.8	2.7	4.3	5.7	20.0	18.7	17.0
	s	1.3	0.6	0.7	0.3	0.2	0.3	0.8	1.5	2.1
	n	10	10	10	5	5	5	5	5	5
2.9% T292	$\bar{x}$	78.2	76.3	74.0	2.5	4.1	5.6	19.5	18.0	16.7
	s	1.8	0.3	1.8	0.1	0.2	0.4	1.7	2.0	1.6
	n	10	10	10	5	5	5	5	5	5
0.5% T292	$\bar{x}$	80.8	78.0	76.0	2.3	3.8	5.3	19.0	17.2	16.2
	s	2.0	0.7	2.1	0.1	0.1	0.2	1.2	0.7	0.8
	n	10	10	10	5	5	5	5	5	5
5.0% I 1010	$\bar{x}$	79.1	76.8	75.0	2.4	3.9	5.5	23.0	21.0	17.5
	s	0.1	1.5	1.9	0.3	0.2	0.5	1.1	0.9	0.6
	n	10	10	10	5	5	5	5	5	5
2.0% I 1010	$\bar{x}$	80.8	78.3	76.1	2.2	3.7	5.3	22.0	19.5	16.0
	s	0.5	0.6	1.0	0.2	0.1	0.1	2.0	0.9	1.1
	n	10	10	10	5	5	5	5	5	5
0.5% I 1010	$\bar{x}$	81.5	79.5	77.5	2.1	3.4	4.7	20.0	19.2	16.1
	s	0.8	0.7	1.1	0.3	0.3	0.2	1.6	1.5	1.2
	n	10	10	10	5	5	5	5	5	5
20% 25/75 T292/T328	$\bar{x}$	80.6	78.0	75.4	2.6	4.2	5.8	19.0	18.0	16.0
	s	0.8	0.9	1.1	0.3	0.2	0.1	1.1	1.2	0.3
	n	10	10	10	5	5	5	5	5	5
20% 50/50 T292/T328	$\bar{x}$	80.0	77.5	74.4	2.6	4.2	5.8	20.2	17.2	16.5
	s	0.9	0.9	2.1	0.1	0.2	0.1	0.9	0.8	1.1
	n	10	10	10	5	5	5	5	5	5
20% 75/25 T292/T328	$\bar{x}$	79.3	75.5	74.8	2.8	4.0	5.6	19.5	18.0	16.5
	s	1.1	1.3	1.8	0.6	0.7	0.4	1.9	2.0	3.0
	n	10	10	10	5	5	5	5	5	5

Sample		Brightness %			Tensile (Kg/1" strip)			Tear (g/sheet)			Burst (psi)			Fold (cycles)		
		2 mrad	5 mrad	10 mrad	2 mrad	5 mrad	10 mrad	2 Mrad	5 Mrad	10 Mrad	2 mrad	5 mrad	10 mrad	2 mrad	5 mrad	10 Mrad
Cotton	$\bar{x}$	79.5	76.5	76.4	2.25	2.15	2.00	49	48	46	10.2	9.5	9.0	308	282	258
	s	3.4	3.1	2.0	0.16	0.12	.13	3.8	3.1	4.2	1.0	1.8	2.1	21	26	22
	n	10	10	10	10	10	10	6	6	6	5	5	5	10	10	10
Bleached S.W.	$\bar{x}$	66.1	66.0	62.2	3.10	3.00	2.80	58	48	41	35	29	26	195	164	147
	s	8.1	2.0	3.1	0.12	0.17	0.11	4.5	2.8	3.8	2.8		4.2	18	21	16
	n	10	10	10	10	10	10	6	6	6	5	5	5	10	10	10
UnBleached S.W.	$\bar{x}$	21.5	22.8	22.0	3.20	3.10	3.00	63	51	48	35	31	27	423	386	356
	s	2.1	2.6	3.7	0.08	0.15	0.16	4.7	2.5	3.5	5.4	8.6	2.1	19	33	18
	n	10	10	10	10	10	10	6	6	6	5	5	5	10	10	10
Groundwood	$\bar{x}$	48.3	46.9	47.0	1.30	1.15	1.10	32	31	29	8.5	8.0	6.8	72	63	55
	s	2.3	3.8	2.1	0.15	0.09	0.13	2.1	3.8	2.7	3.1	8.8	3.1	17	36	12
	n	10	10	10	10	10	10	6	6	6	5	5	5	10	10	10

Kappa No.

Cotton – 0
Bleached S.W – 12.3
U.B. S.W. – 38.6
Groundwood – 56.1